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<table>
<thead>
<tr>
<th>No</th>
<th>Paper</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Author(s)</td>
<td>Title</td>
</tr>
<tr>
<td>-----</td>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>27</td>
<td>Li S. X., Ren X. D and Li J.</td>
<td>A random medium model for simulation of concrete failure.</td>
</tr>
<tr>
<td>32</td>
<td>Ren X. D., Li J.</td>
<td>Multi-scale based fracture and damage analysis of steel fiber reinforced concrete.</td>
</tr>
</tbody>
</table>
On methods for extending a single footfall trace into a continuous force curve for floor vibration serviceability analysis

Jun Chen*, Yixin Penga and Ting Yeb

State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, 200092, Shanghai, P.R. China

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Abstract. An experimentally measured single footfall trace (SFT) from a walking subject needs to be extended into a continuous force curve, which can then be used as load for floor vibration serviceability assessment, or on which further analysis like discrete Fourier transform can be conducted. This paper investigates the accuracy, applicability and parametrical sensitivity of four extension methods, Methods I to IV, which extends the SFT into a continuous time history by the walking step rate, stride time, double support proportion and the double support time, respectively. Performance of the four methods was assessed by comparing their results with the experimentally obtained reference footfall traces in the time and frequency domain, and by comparing the vibrational response of a concrete slab subjected to the extended traces to that of reference traces. The effect of the extension parameter on each method was also explored through parametrical analysis. This study finds that, in general, Method I and II perform better than Method III and IV, and all of the four methods are sensitive to their extension parameter. When reliable information of walking rate or gait period is available in the test, Methods I or II is a better choice. Otherwise, Method III, with the suggested extension parameter of double support time proportion, is recommended.

Keywords: single footfall trace; extension method; motion capture technology; floor vibration serviceability

1. Introduction

Human walking load is a kind of dynamic excitation that may, if not properly considered in the structural design, cause a vibration serviceability problem to structures like footbridges, cantilever stands in stadiums and long-span floors. It may also cause dysfunction of vibration sensitive devices in high-tech factories, labs or hospitals (Pavic and Reynolds 2002, Ebrahimpour and Sack 2005, Han et al. 2009, Nguyen et al. 2012). One of the well-known examples is the London Millennium Bridge which experienced, on its opening day, excessive vibration when a large number of people were moving on the bridge. The bridge was then closed for almost two years until engineers figured out reasons for the uncomfortable swaying motion and installed some expensive dampers to abate the vibration (Dallard et al. 2001, Strogatz et al. 2005).
Optimal determination of frequencies in the spectral representation of stochastic processes

Jianbing Chen · Jie Li

1 Introduction

Dynamic excitations in engineering practice, such as ground motion, strong wind and sea wave, etc., exhibit strong uncertainties and thus should be regarded as stochastic processes. Mathematically, complete information of a stochastic process could be specified by the family of finite-dimensional joint probability distributions. However, these joint distributions are usually unavailable in most practical problems. Fortunately, for second-order stationary processes, the first and second-order statistics, i.e. the mean and the auto-correlation function (or equivalently, the power spectral density function (PSD for short)), are adequate to capture their dominant property [3]. Particularly, the PSD is widely adopted in modeling of stochastic processes in engineering disciplines including earthquake, wind and ocean engineering, etc [17]. For instance, in earthquake engineering, the employment of PSD dates back to Housner in his pioneering work regarding the ground acceleration as a white noise process [13], while Kanai’s research in 1957 founded the basic framework for employing and improving PSD models for ground motion by introducing the mechanism of filtering by site soil [14,26]. From then on, a variety of studies have been carried out on the modeling of ground motions, from both the aspect of improving PSD models [5,6] and the aspect of identifying basic parameters via measured data [16]. These investigations set up a solid foundation for the PSD modeling of ground motion.

In the stochastic response analysis and reliability assessment of linear structures, the PSD of input is adequate because the PSD of response can be obtained via the theory of random vibration [17,20]. In some other cases, however, particularly for nonlinear structures, the time history of a stochastic process, or more exactly, the explicit representation of a stochastic process, is necessary as input. A variety of methods have been developed and applied. Among them the widely known ones are the Karhunen-Loève decomposition [8,12], the sampling representations [10], the Poisson-distributed harmonic combination [9] and the spectral representation method [24], etc. These methods essentially provide different types of random function description for a stochastic process [18,23]. Due to its clarity in theory and simplicity in implementation, the spectral representation method was widely employed. In this method, a stationary stochastic process is represented by the summation of a number of harmonic components with different deterministic frequencies and independent random phases uniformly
IMPROVING POINT SELECTION IN CUBATURE BY A NEW DISCREPANCY

JIANBING CHEN† AND SHENGHAN ZHANG†

Abstract. Reasonable point set selection is of paramount importance to the accuracy of high-dimensional integrals that will be encountered in various disciplines. In the present paper, to improve the point selection and to overcome the computational complexity of evaluating classical discrepancies, the concept of extended F-discrepancy (EF-discrepancy) and generalized F-discrepancy (GF-discrepancy) of a point set is introduced and justified by comparative studies with other existing discrepancies. Meanwhile, the extensions of the Koksma–Hlawka inequality for EF-discrepancy are proved and a conjecture for GF-discrepancy is put forward and discussed. This GF-discrepancy is then employed as the objective function when selecting the optimal rotation angles in the rotation transform of the quasi-symmetric point method (Q-SPM). Meanwhile, it is also proved that the rotation transform will keep the degree of algebraic accuracy. A genetic algorithm is adopted to solve the optimization problem. Several numerical examples are elaborated, demonstrating that the GF-discrepancy is a reasonable index in judging the goodness of a point set and that the optimal rotation of Q-SPM will greatly improve the accuracy of stochastic analysis of nonlinear structures. The proposed GF-discrepancy and the resulting rotational Q-SPM point sets could be applied directly to other problems of uncertainty quantification. Problems to be further studied are discussed.

Key words. cubature, generalized F-discrepancy, quasi-symmetric point method, rotation transform, genetic algorithm, probability density evolution method

AMS subject classifications. 65D32, 74H50

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1. Introduction. High-dimensional integrals are encountered in various science and engineering disciplines, particularly when stochastic phenomena are addressed, e.g., finance [13], uncertainty quantification of various physical and engineering systems [26], and stochastic dynamics [3, 14]. A variety of methods, usually called cubature formulae [8], have been developed in recent decades. The cubature formulae generally adopt a weighted summation of a series of function values at a specified point set as an approximation of the target high-dimensional integral. Basically, they could be classified into two types: (1) the type in which the point set is determined by prescribing the degree of algebraic accuracy, e.g., the Gaussian quadrature, the sparse grid method [22], and the quasi-symmetric point method (Q-SPM) [23], and (2) the type in which the point set is generated by some sampling techniques to achieve uniformity to a degree. The latter includes methods adopting random points, e.g., Monte Carlo methods [20] and their improvements, and methods adopting deterministic points, e.g., the number theoretical method (NTM), also known as the quasi Monte Carlo method in the literature [12, 13, 17].
Stochastic Harmonic Function Representation of Stochastic Processes

An approach to represent a stochastic process by the combination of finite stochastic harmonic functions is proposed. The conditions that should be satisfied to make sure that the power spectral density function of the stochastic harmonic function process is identical to the target power spectral density are firstly studied. Then, two kinds of stochastic harmonic functions, of which the distribution of the amplitudes and the random frequencies are different, are discussed. The probabilistic characteristics of the two kinds of stochastic harmonic functions, including the asymptotic distribution, the one-dimensional probability density function, and the rate of approaching the asymptotic distribution, etc., are studied in detail by theoretical treatment and numerical examples. Responses of a nonlinear structure subjected to strong earthquake excitation are investigated. The studies show that the proposed approach can capture the target power spectral density exactly with any number of components. The reduction of the components provides flexibility and reduces the computational cost. Finally, problems that need further investigations are discussed.

Keywords: stochastic harmonic function, stochastic process, power spectral density, probability density function

1 Introduction

Stochastic dynamics has gained increasing interest in the past decades and has been extensively studied [1–3]. The relationship for linear systems between the probabilistic information of the input and the output, particularly the elegant transfer relationship of the power spectral density (PSD) functions [4], marks the importance of modeling of the stochastic excitations, which is the basic prescribed known information. However, the nonlinear stochastic dynamics is much more involved. Actually, the simple transfer relationship of the PSD does not exist for general nonlinear systems. In these cases, an explicit random function expression, rather than the PSD, of the stochastic excitation in terms of some basic random variables is usually necessary.

Generally speaking, mathematically the finite-dimensional probability density functions (PDFs) are introduced to describe the complete information of a stochastic process [5]. Because in practice the finite-dimensional probability density functions are unavailable for most stochastic processes, the second order statistical characteristics, e.g., the PSD or the covariance function, are usually adopted. However, the explicit expression of a stochastic process in terms of the involved random basic variables is still unspecified. Actually, a stochastic process \( X(\tau, t) \) can also be regarded as a function of both the random event \( \sigma \) and the time \( t \), which means another description of stochastic processes in which the probabilistic information of the \( \sigma \) is to be specified if the explicit expression of the random function \( X(\tau, t) \) is known [6]. To this end, two methodologies have been studied. The first is physical modeling where the physical mechanism of a stochastic excitation is taken into account to determine the explicit expression of the random function and then the observed data are adopted to identify the distribution of the involved basic random variables [7]. The second is some kind of mathematical expansion, including, say the Karhunen-Loève decomposition [8,9], the double-orthogonal decomposition [10], the sampling representations [11], the combination of random number of harmonic components [12], and the spectral representation method [13], etc. One of the greatest disadvantages of the mathematical expansions is that almost all of them involve truncation of an infinite series for practical applications, which will lead to truncation error and thus the probabilistic information of the generated stochastic process deviates from the target stochastic process. For instance, to make the PSD of the generated stochastic process approximate the target PSD in an acceptable accuracy, usually hundreds of harmonic components should be retained in the truncated series in the most widely-used classical spectral representations [14], which will lead to involving hundreds of random variables. As is known, handling a large number of random variables is always cumbersome and, consequently, to reduce the number of retained terms is of paramount significance [15]. Another disadvantage of the above mathematical expansions is that it might be hard to capture the distribution information of the generated stochastic process.

In the present paper, a family of stochastic harmonic functions (SHFs) for the representation of stochastic processes with a
Tuned rolling-ball dampers for vibration control in wind turbines

Junling Chen a,*, Christos T. Georgakis b

a Department of Building Engineering, Tongji University, Shanghai 200092, China
b Department of Civil Engineering, Technical University of Denmark, Building 118, Brovej, 2800 Kongens Lyngby, Denmark

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A B S T R A C T

With wind turbines growing in size and cost, it is necessary to reduce their dynamic responses and improve their fatigue lifetime. A passive tuned-mass damper (TMD) is a very efficient solution for vibration control in structures subjected to wind excitations. In this study, a tuned rolling-ball damper characterized by single or multiple steel balls rolling in a spherical container is proposed to be mounted on the top of wind turbines to reduce the wind-induced vibration. A 1/20 scale shaking table model was developed to evaluate the control effectiveness of the damper. The wind-induced dynamic responses of the test model with and without TMD were obtained from the shaking table tests. The test results indicated that the rolling-ball dampers could effectively suppress the wind-induced vibration of wind turbines. The damper with three balls in one container had better control effectiveness than that with only one ball because of the impact effect and the rolling friction. The control effectiveness of the damper cannot be improved further when the number of balls is increased beyond a certain point.

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1. Introduction

Wind energy is an important part of the global push for clean, renewable energy alternatives. In recent years, the wind turbine tower has grown from 40 m to 100 m with turbine sizes reaching 3.0 MW. Taller towers are desirable because winds are stronger at higher altitudes, thereby producing more power for each turbine installed. The cost of a tower is generally beyond 20 percent of the total cost of a wind turbine. Therefore, it is quite important for the final cost of energy to build towers as optimally as possible. Wind turbines present complex structure problems in the context of natural wind due to the interaction of the rotating blades and the tower. The wind speed and direction do not only vary with time, but also with the swept area. For offshore wind turbines, the influence of wave loads makes their dynamic response more complex. However, because of the slenderness of wind turbine towers, the coupling of wind and wave loads may produce excessive vibrations that will inhibit the mechanical system in the nacelle to convert wind energy into electrical energy and makes support structures susceptible to fatigue damage. Therefore, the vibration control of wind turbine towers is an important issue for the development of wind energy.

Nowadays passive vibration control is a mature technology and the tuned mass damper (TMD) is one of the simplest and the most reliable passive control devices. The application of TMD for tall buildings under wind or earthquakes has been extensively investigated. Park and Reed [1] showed that the uniformly distributed mass system was more effective in...
A boundary element analysis of fatigue crack growth for welded connections under bending

Tao Chena,⇑, Zhi-Gang Xiaob, Xiao-Ling Zhao c, Xiang-Lin Gua

aDepartment of Building Engineering, Tongji University, Shanghai 200092, China
bSchool of Applied Sciences and Engineering, Monash University, Churchill, VIC 3842, Australia
cDepartment of Civil Engineering, Monash University, Clayton, VIC 3800, Australia

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Transverse fillet welded joints and circular hollow section (CHS)-to-plate welded connections were analyzed to obtain crack growth life under bending. Based on a 3D boundary element model, an initial semi-elliptical surface crack was embedded at the weld toe. Thereafter, crack propagation was performed with Paris' law and strain energy density criterion. This method discards the assumption of constant aspect ratio of crack shape during propagation stage. Numerical results were compared with the experimental results in the literature. It is found that numerical analysis is reliable and the boundary element method is suitable for estimating the fatigue crack growth life.

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1. Introduction

Fatigue performance of welded connections is essential to the integrity of metallic structures that are subjected to fatigue loading. Based on fatigue tests, guidelines have been established for the welded connections [1–4]. Structural stress is usually employed for design purpose [5]. However, small defects and initial cracks are inevitable for these welded connections. Fatigue life of the welded connections is identified as the crack propagation life [6]. Consider the fact that it is expensive to manufacture specimens and conduct fatigue tests, numerical analysis for crack propagation is necessary to have a better understanding of the welded connections. It is accepted that the fracture mechanics method is a reliable approach for the crack growth life prediction under fatigue loading.

The crack propagation analysis is usually conducted with Paris law [7], and a reliable stress intensity factor (K) is required. Previous researches show that the stress intensity factors are difficult to obtain through experimental or theoretical analysis. Close form solutions for stress intensity factors are often insufficient for complicated practical components such as the circular hollow steel tubes [8]. To solve this problem, numerical analysis has been employed. The numerical analysis is usually conducted with the finite element method and the crack shape and crack path have to be determined before modeling [9,10]. It requires a very extensive 3D element mesh with crack tip elements. Therefore, different kinds of assumptions or fatigue tests have to be conducted to find out the crack shape and crack path. The crack is usually assumed to be a semi-elliptical crack with a fixed aspect ratio [10,11]. This is not true since the crack shape can change with the crack propagation. Fatigue tests of transverse welded joints under bending revealed that the ratio of the crack depth to crack length on the surface varies with fatigue loading cycles [12]. The boundary element method (BEM) has been employed as an efficient numerical method to solve crack propagation together with the technique of dual boundary element method (DBEM) [13–15]. This
Modified equation for stability computation of round HSS beam–column subject to biaxial moments

Yiyi Chen a, Baiping Dong b,∗

a State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
b Department of Civil Engineering, Tongji University, Shanghai 200092, China

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A B S T R A C T

This paper presents the study on equations for stability capacity computation of round hollow structural section (HSS) beam–column subject to axial compression and biaxial moments about two principal axes. By the comparison of numerical results with design interaction formula in major design codes around the world, it is shown that existing design interaction formulas have limitations in stability capacity calculation of HSS beam–column under biaxial moments. Based on theoretical and numerical analysis, an alternative method together with a modified equation is proposed to predict the stability capacity of round HSS beam–columns. The modified equation is verified to be accurate and applicable to various biaxial moment distributions.

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1. Introduction

Round and square hollow structural section (HSS) members are being used in more building structures in recent years for their prominent feature in architecture aesthetics and structural efficiency particularly for structural columns. Columns in building frames are usually subject to axial compression and end bending moments orthogonal about two principal axes simultaneously; they are beam–column members. Undoubtedly, stability capacity computation of such beam–column members is essential in the design process.

There has been extensive research done on stability capacity computation of beam–column members [1–4]. The instability problem of a beam–column subject to axial compression and bending moments about two perpendicular principal axes is classified as the non-bifurcation type of instability [4]. In this case, the critical loading condition is reached when the most critical section of the member reaches its capacity limitation, and the maximum load on the full load–deformation curve is the stability capacity of the beam–column. However, coupled biaxial moments, geometric nonlinearities, and material plasticity all together make it difficult to establish a simple and accurate design formula to predict the stability capacity for beam–columns.

Interaction formulas for beam–column subject to axial compression and biaxial moments given in existing design codes, GB50017 [5], Eurocode3 [6], ANSI/AISC360 [7], and AS4100 [8] were developed from the interaction formula for a beam–column subject to axial compression and bending moment about one principal axis; these interaction formulas are proved valid in practice when they are applied to beam–columns with H shaped sections (wide-flange shapes). Since these design formulas were not developed particularly for HSS beam–columns, they generally under-predict the stability capacity of round HSS beam–columns subject to biaxial moments by a wide margin; and there are no complete studies presented in the literature on the stability capacity calculation of round HSS beam–columns subject to biaxial bending moments.

This paper studies the stability of HSS beam–columns subject to compression and biaxial bending and proposes an interaction formula suitable for accurately predicting their stability capacity. First, the characteristics and behavior of round HSS beam–columns are discussed. Next, existing design interaction formulas around the world are summarized and discussed. After that, a numerical model suitable for determining the stability capacity of round HSS beam–columns subject to compression and biaxial bending is described and validated with test results. Then, the stability capacity of round HSS beam–columns is obtained through numerical simulation and the results are compared with the prediction from existing design interaction formulas. A new method is then proposed to calculate the stability capacity of round HSS beam–columns subject to biaxial bending and compression that gives better agreement to the numerical results. The proposed
An overview study on cross-section classification of steel H-sections

Yiyi Chen, Xin Cheng, David A. Nethercot

State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
Department of Civil and Environmental Engineering, South Kensington Campus, Imperial College London SW7 2AZ, UK

Abstract

A review is made of the treatment of cross-sectional classification in four major current design specifications (Eurocode, AISC, AIJ and Chinese Codes) including both the non-seismic and seismic cases. Three rules, namely 'individual plate rule', 'limited load pattern rule' and 'monotonic rule' are present in most of the specifications but these rules neglect the effect of some important interactive behavior. A review of the research base, paying particular attention to interactive effects and design criteria under complex load patterns, provides sufficient evidence for the conclusion that web–flange interaction, the axial force ratio, different bending axes and cyclic loading are significant features that influence cross-sectional behavior but have received little consideration. Thus, the necessity for current specifications to improve those rules has been highlighted. Finally the paper assesses the needs for future research to effect the significant improvements that would appear to be necessary for classifying cross-sections.

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Contents

1. Introduction ........................................................................... 387
2. Review of cross-section classification rules of different specifications ................................................. 387
2.1. Definition of cross-section classification ............................................................. 387
2.2. Treatment of cross-section classification in different specifications ............................................... 387
2.2.1. Eurocode ........................................................................................................ 387
2.2.2. AISC ............................................................................................................... 388
2.2.3. AIJ .................................................................................................................. 388
2.2.4. Chinese Codes ................................................................................................. 388
2.3. Comparisons of slenderness limits for H-sections in each specification .................................... 388
2.4. Summaries of comparing and contrasting results ........................................................................... 389
2.4.1. Individual plate rule ....................................................................................... 389
2.4.2. Limited load pattern rule .............................................................................. 389
2.4.3. Monotonic rule .............................................................................................. 390
3. Review of research base .............................................................. 390
3.1. Monotonic loading ....................................................................................... 390
3.1.1. Stub columns ................................................................................................. 390
3.1.2. Beams and beam–columns bent about the strong axis .................................. 390
3.1.3. Beams and beam–columns bent about the weak axis .................................... 391
3.2. Cyclic loading ................................................................................................. 391
3.2.1. Difference between monotonic loading and cyclic loading ............................... 391
3.2.2. Cross-section classification of H-sections under cyclic loading ..................... 391
4. Expectations from future research ................................................ 392
5. Conclusions ............................................................................ 392
6. Symbols .................................................................................. 393
Acknowledgment ........................................................................ 393
References .................................................................................. 393
Effect of Loading Protocols on the Hysteresis Behaviour of Hot-Rolled Structural Steel with Yield Strength up to 420 MPa

Yiyi Chen1,*, Wei Sun2 and Tak-Ming Chan3

1State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China
2College of Civil Engineering, Tongji University, Shanghai, China
3School of Engineering, University of Warwick, Coventry, United Kingdom

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Abstract: This paper presents a series of material tests on hot-rolled structural steel with nominal yield strength ranging from 235 MPa to 420 MPa to study the effect of loading protocols, material thickness and yield strength on the hysteresis behaviour. A total of seven tensile coupon tests were conducted and a total of twenty one experiments were conducted in cyclic axial configuration on hot-rolled structural steel. Three different cyclic loading protocols were adopted namely, Cyclic Ascend, Cyclic Alternate and Cyclic Tensile with strain amplitudes varying between $\pm0.5\%$ to $\pm2\%$. The results of the hysteretic responses at different loading protocols were presented and compared. The results revealed the non-masing and accumulated strain-hardening behaviour of the tested materials and the effect of material thickness and yield strength on the characteristics of hysteretic response was minimal. The loading protocols affect the hysteresis behaviour but are insignificant for seismic applications within the range of the strain in the tests.

Key words: cyclic tests, hysteresis loops, loading protocol, material tests, steel.

1. INTRODUCTION

The response of steel structures under extreme seismic conditions is governed by their geometry and by the hysteretic behaviour of the steel materials. The random nature of the seismic waves may also impose non-uniform straining histories on structures at material level. Better understanding of material cyclic behaviour is thus crucial for determining the suitability of a material for seismic applications. This paper investigates the response of hot-rolled structural steel materials with nominal yield strength between 235 MPa to 420 MPa under different loading protocols through cyclic material tests with variable strain amplitude between $\pm0.5\%$ to $\pm2\%$. Previous researchers (Dusicaka et al. 2007) investigated the hysteretic response of five different plate steels under repeated cyclic plastic axial strains with a maximum $\pm7\%$ strain amplitude. The results revealed that the cyclic stress for structural steels (with nominal yield strength of 345 MPa, 440 MPa and 485 MPa) increased up to $2.0 \times$ monotonic yield strength while for low-yield point steels (with nominal yield strength of 100 MPa and 225 MPa), the cyclic stress can be increased up to $4.8 \times$ monotonic yield strength. The results also indicated that, irrespective of the monotonic yield strength, steel types of similar manufacturing specification tend towards the same cyclic stress-strain response under repeated inelastic strain. Wu et al. (2007) and Shen and Wu (2009) conducted experimental investigations on the monotonic tensile and low cycle fatigue properties of hot-rolled structural steel materials with minimum yield strength of 225 MPa and 325 MPa and proposed an analytical fatigue model.

*Corresponding author. Email address: yiyichen@tongji.edu.cn; Fax: +862165984976; Tel: +862165983300.
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Experimental study on H-shaped steel beam-columns with large width-thickness ratios under cyclic bending about weak-axis

Xin Cheng\textsuperscript{a}, Yiyi Chen\textsuperscript{a, *}, David A. Nethercot\textsuperscript{b}

\textsuperscript{a} State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
\textsuperscript{b} Department of Civil and Environmental Engineering, South Kensington Campus, Imperial College London, SW7 2AZ, UK

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\textbf{A B S T R A C T}

This paper presents the findings from an experimental study of nine H-shaped steel beam-columns with large width-thickness ratios subjected to combined constant axial force and cyclic bending about the weak-axis. Considering different categories of cross-sections, various width-thickness ratios for the flange and web of the specimens are selected, and a reliable structural testing system is developed. The test results show that local buckling dominates the failure mechanism of all the specimens without overall buckling being observed. For bending about the weak-axis, the H-shaped steel members exhibit favorable plastic deformability, and it is concluded that the classification rules in the current design specifications for H-sections are unsuitable for weak-axis bending scenarios. In addition, it is found that the effects of the flange/web width-thickness ratios as well as the axial force ratios on the hysteretic behavior are strongly dependent on each other, and thus should be considered in an interactive way.

\begin{align*}
R_h &= \frac{\theta_y}{\theta_u} \\
R_p &= \frac{M_p}{M_u} \\
M_{pc} &= M_{pe} \geq M_{pl}
\end{align*}

\textsuperscript{*} Corresponding author. Tel.: +86 65982926.
E-mail address: yiyichen@tongji.edu.cn (Y. Chen).

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1. Introduction

H-shaped steel beam-columns have been frequently used in structural steel frameworks, and have been extensively studied in the past 50 years. In terms of their susceptibility to local buckling, H-shaped steel beams and beam-columns are normally categorized into four classes in the current design codes, e.g. EC3 [1], as illustrated in Fig. 1. For a class 4 cross-section, local buckling occurs prior to the attainment of the elastic moment resistance \(M_{el} < M_{pl}\). A class 3 cross-section is one in which local buckling occurs after reaching the elastic moment resistance but before the plastic moment resistance \(M_{el} \leq M_{el} < M_{pl}\). A class 2 cross-section corresponds to one which can reach its plastic moment resistance but with limited rotation capacity due to local buckling \(M_{el} \geq M_{pl}\). Finally for a class 1 cross-section, the plastic moment resistance can be developed with sufficient rotation capacity to allow redistribution of moments in the steel frames \(M_{el} > M_{pl}\) and \(R > R_0\). In the above definitions, \(M_{el}\) is the ultimate moment resistance of the cross-section; \(M_{pl}\) and \(M_{pc}\) are the elastic and plastic moment resistance respectively, including the effect of axial force; \(R = \theta_y/\theta_u\) is the yield rotation; and \(R_0\) is the required rotation capacity, which is defined slightly differently in each specification.

Until now, class 1 and class 2 H-sections have been widely investigated. Considering the scenarios of H-sections under combined compression and strong-axis bending, Nakashima et al. [2–4], Kato [5] and Gioncu and Petcu [6,7] examined the monotonic behavior including both strength and ductility thoroughly, and moreover, Lee and Lee [8], Hsu and Shyu [9] and Newell and Uang [10] presented experimental investigations into the effect of cyclic bending on the strength and rotation capacity of such members. It was pointed out that the governing parameters are the flange and the web slendernesses and the axial force ratio. With respect to the research on class 1 and class 2 H-sections under combined compression and weak-axis bending, emphasis has been mainly given to the monotonic behavior. The research of Bradford and Azhari [11], Kim and Chen [12] and Zubydan [13] on the monotonic weak-axis behavior of class 1 or class 2 H-sections suggested that the plastic strength curve for weak-axis bending in AISC-360-05 [14] is quite conservative.

As more recently recognized, considerable economic benefits may be derived from adopting class 3 (semi-compact) and class 4 (slender) members, denoted as SC–S members in this paper, because they possess better overall stability and larger moment resistance than those with class 1 or class 2 cross-sections of equivalent weight. Contributions have been made by Hasham and Rasmussen [15] and Kim et al. [16] towards the method of calculating the ultimate strength of SC–S H-section members under combined monotonic compression and strong-axis bending. Avery [17,18] investigated steel frames composed of SC–S H-section members...
Wind Tunnel Study on Wind-Induced Vibration Responses of a UHV Transmission Tower-Line System

H.Z. Deng, R.J. Si, X.Y. Hu and C.Y. Duan*

Department of Building Engineering, Tongji University, Shanghai 200092, China

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Abstract: This paper presents an experimental investigation on the wind-induced vibration of a transmission tower-line system. A discrete stiffness method is applied to design the aero-elastic model on the basis of similarity theory. The dynamic characteristics of the single tower and the tower-line system are identified and the displacement responses at different positions are obtained under a variety of wind speeds. The mean and the RMS of the displacements as well as their spectra are discussed. Moreover, the test results and the codal specifications are compared in terms of the wind-induced vibration coefficient. The first natural frequency of the single tower is slightly larger than that of the tower-line system. But the damping ratio of the former is smaller than that of the latter, especially in the direction normal to the conductors. At the wind attack angle of 90°, the conductors significantly increase the longitudinal and lateral displacement RMS as well as the longitudinal mean displacement. And more complicated forms of vibration are aroused by the conductors, especially in the lateral direction. The wind-induced vibration coefficient show a notable rise at the position of cross arm, which cannot be characterized by Chinese code. Besides, the wind-induced vibration coefficient specified by the code is much smaller than test results thus the codal value seems to be unsafe for the UHV transmission tower.

Key words: wind tunnel test, wind-induced vibration, aero-elastic model, transmission tower-line system, wind-induced vibration coefficient.

1. INTRODUCTION

In recent years, a number of ultra high-voltage (UHV) transmission lines are planned to be constructed in China. The Ximeng-Nanjing and the Huainan-Shanghai 1000 kV UHV transmission lines are already in early design stage. The UHV transmission lines, compared to 500 kV or 220 kV ones, usually have taller height, longer cross arms, larger conductors and stronger supporting members. As a consequence, natural frequencies of a UHV tower would be lower than a traditional one given similar other conditions. Besides, the first torsional frequency of the UHV tower tends to be close to the first bending frequency. It suggests that the coupling effect of bending modes and torsional modes is more likely to occur in UHV tower. This effect would be further excited since the UHV tower usually has larger conductors thus the wind loads and oscillations of the conductors would be more prominent. Therefore, it is an urgent issue to investigate the wind-induced response of UHV transmission tower.

In Chinese code (GB50009 2006), the concept of wind-induced vibration coefficient is proposed to take account of the effect of fluctuating wind load, i.e., the design wind load is obtained by multiplying the static...
Prediction of ground vibration due to the collapse of a 235 m high cooling tower under accidental loads

Feng Lin a, Yi Li a, Xianglin Gu a,*, Xinyuan Zhao a, Dongsheng Tang b

a Department of Building Engineering, Tongji University, No. 1239 Siping Road, Shanghai 200092, China
b Guangdong Electric Power Design Institute, No. 1 Tianfeng Road, Guangzhou, Guangdong 510663, China

HIGHLIGHTS

- Ground vibration due to the collapse of a huge cooling tower was predicted.
- Accidental loads with different characteristics caused different collapse modes.
- Effect of ground vibration on the nuclear-related facilities cannot be ignored.

ABSTRACT

A comprehensive approach is presented in this study for the prediction of the ground vibration due to the collapse of a 235 m high cooling tower, which can be caused by various accidental loads, e.g., explosion or strong wind. The predicted ground motion is to be used in the safety evaluation of nuclear-related facilities adjacent to the cooling tower, as well as the plant planning of a nuclear power station to be constructed in China. Firstly, falling weight tests were conducted at a construction site using the dynamic compaction method. The ground vibrations were measured in the form of acceleration time history. A finite element method based “falling weight-soil” model was then developed and verified by field test results. Meanwhile, the simulated collapse processes of the cooling tower under two accidental loads were completed in a parallel study, the results of which are briefly introduced in this paper. Furthermore, based on the “falling weight-soil” model, “cooling tower-soil” models were developed for the prediction of the ground vibrations induced by two collapse modes of the cooling tower. Finally, for a deep understanding of the vibration characteristics, a parametric study was also conducted with consideration of different collapse profiles, soil geologies as well as the arrangements of an isolation trench. It was found that severe ground vibration occurred in the vicinity of the cooling tower when the collapse happened. However, the vibration attenuated rapidly with the increase in distance from the cooling tower. Moreover, the “collapse in integrity” mode and the rock foundation contributed to exciting intense ground vibration. By appropriately arranging an isolation trench, the ground vibration can be significantly reduced.

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1. Introduction

In earthquake-prone areas, seismic design should be carefully performed for the design of a nuclear power station (Bommer et al., 2011). However, the ground vibration due to the collapse of a huge structure, e.g., a cooling tower, is usually not considered. With increases in the height and mass of a tower-like structure, the ground vibration may become more intensive when collapse happens. Hence, it is reasonable to be concerned about whether this kind of ground vibration may damage the safe operation of nearby nuclear-related facilities. Unfortunately, this particular issue has not been given serious attention, as few studies have addressed it.

As a contribution to the mentioned problematic concern, this study presents a comprehensive approach for the prediction of the ground vibration due to the collapse of a cooling tower. The study motivation comes from a new water cooling tower with an overall height of 235 m, which will be built as a part of the construction of a planned nuclear power station in southern China. A cooling tower of such a great height, probably the highest planned one worldwide, raises a number of questions. One of the most interesting issues is the proper prediction of collapse-induced ground vibrations, because the planned cooling tower is to be adjacent to the nuclear island with their spacing to be about 200 m, which is also the usual distance for other planned nuclear power stations in China due to limited space. In the event of the collapse of the
A modified rigid-body-spring concrete model for prediction of initial defects and aggregates distribution effect on behavior of concrete

Xianglin Gu *, Li Hong, Zhuolin Wang, Feng Lin

Department of Building Engineering, Tongji University, Shanghai 200092, PR China

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A B S T R A C T

A modified rigid-body-spring concrete model was developed by considering the contact between elements after the failure of the springs. The discretization and definition of elements and springs were based on the three phases of concrete, including the coarse aggregates, the mortar and their interface. Based on the modified rigid-body-spring model, stress–strain curves and failure modes of concrete specimens with preset holes under uniaxial loads were simulated firstly, the simulated results were validated by those obtained from tests; and then, the effect of initial defects and distribution of coarse aggregates on mechanical behavior of concrete were investigated. It was found that with the increase of initial defects amount, the strength, elastic modulus and Poisson’s ratio of concrete decreased nonlinearly; and, the statistical analysis revealed that variability of the mechanical properties of concrete was mainly affected by the random distribution of coarse aggregates.

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1. Introduction

Concrete, as a highly heterogeneous material, has complicated fracture mechanisms, which is strongly affected by its meso-structure, such as aggregates, mortar, interface between aggregates and mortar and micro-cracks. However, study of these influences has been restricted mostly to experiments. Numerical tools are good options to gain some insight into the problems. Many attempts [1–5] have been made to investigate the fracture process of concrete by mechanical model at meso-level.

Rigid-body-springs model (RBSM), which is attractive due to its simplicity, freedom in mesh layout and generation, and providing a discrete representation of material disorder and failure [6] is being used to analyze concrete fracture at meso-level [3–5]. Nagai et al. [3,4] have discretized concrete as aggregates, mortar and interfaces between aggregates and mortar with different mechanical properties, and used the static relaxation method to analyze the failure of concrete. Even though neighbor connectivity was defined, there was no special emphasis on contact modeling, which considered the re-contact of an element with neighbor elements. Therefore, some complicated issues, such as nonlinearity in compression and crack closing or reopening in the model could not be considered, which influenced the simulated results to some extent [6].

Remarkably, concrete was always assumed as a three composites material without any initial defect in previous studies [1–5]. However, initial defects are thus inherent to concrete, which have great influence on the properties of concrete, notably its strength [7].

Besides, as we all know that aggregates (including fine and coarse) are the major constituent of concrete and they generally occupy 75–80% of the volume of concrete. Previous studies [8–10] have been carried out to investigate the effect of aggregate characteristics, such as mineralogy, shape, surface texture, size and proportions of aggregates, on the behavior of concrete. Yin et al. [11] found that coarse aggregates distribution has obvious influence on the crack path inside asphalt concrete. Ai et al. [12] investigated the influences of the distribution of crushed aggregates on the failure behavior and strength of heterogeneous polymer concrete. However, researches, especially statistical analysis, focusing on the effect of the random distribution of coarse aggregates on concrete behavior are still limited and its effect is not yet well established.

In this paper, a modified RBSM for concrete is presented, which allows the element relationship conversion from connection to contact to describe the re-contact of an element with neighbor elements; and, the dynamic relaxation procedure of discrete element method is adopted in the simulation to avoid the complex calculation of stiffness matrix in the RBSM. Then, by using the proposed mechanical model, the influence of initial defects (voids and cracks) and random distribution of coarse aggregates on mechanical properties of concrete is investigated in detail. The paper is organized as follows. In Section 2, the proposed model is presented. In Section 3, material properties and calculation parameters are discussed. Section 4 is devoted to the model validation,
Experimental study and application of mechanical properties for the interface between cobblestone aggregate and mortar in concrete

Xianglin Gu*, Li Hong, Zhuolin Wang, Feng Lin

Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, PR China

HIGHLIGHTS

- We examine both the tensile and the shear bond strengths of the interface between cobblestone aggregate and mortar.
- Increasing the normal stress will increase the shear bond strength of the interface.
- Mohr–Coulomb failure theory can be used to illustrate the interfacial failure at meso-level.
- By using the mechanical properties of the interface, the behavior of concrete can be predicted to a degree of accuracy.

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ABSTRACT

The failure mechanism under the combined state of normal and shear stresses for the interface between cobblestone aggregate and mortar was investigated by testing the interfacial bond strength. It was revealed that the tensile bond strength of the interface between cobblestone aggregate and mortar was about half the tensile strength of the mortar, but the shear bond strength of the interface was close to the shear strength of the mortar. Moreover, the shear bond strength increased with increases in the normal stress when the normal stress was smaller than 60% of the compressive strength of the mortar, but it can be assumed that the shear bond strength decreases with increases in the normal stress if it was larger than 60% of the compressive strength of the mortar. The failure criterion for the interface under combined normal and shear stresses was established by regressing the experimental data. Finally, a two-dimensional mesoscopic mechanical model, in which the mechanical properties of the interface were described by the obtained bond strength and failure criterion, was used to simulate the fracture process of concrete. Verification of the simulation was performed by comparing the simulated results with those obtained from the tests, in which the aggregate roughness was similar to that in the interfacial experiment. It was found that, by using the mechanical properties of the interface in the numerical model, the behavior of concrete could be predicted to a reasonable degree of accuracy. The propagation of cracks and the failure modes of concrete can also be determined using the proposed numerical model.

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1. Introduction

It is generally accepted by many researchers that the microstructure of the interface between coarse aggregate and mortar is the weakest link in normal concrete [1,2]. Therefore, the mechanical behavior of concrete is significantly affected by the properties of the interface [3,4].

In the mesoscale, concrete is idealized as stiff aggregates embedded in a soft matrix and separated by a weak interface [5]. Moreover, it has been proven that the study of concrete at the mesoscale is the most practical and useful method for the evaluation of its mechanical properties [6]. Attempts have been made to model concrete analytically at the mesoscale.

The mechanical properties of each phase have a significant effect on crack initiation and propagation. In particular, the accurate understanding of the properties and behavior of the interface is one of the most important issues in mesoscale analyses, because cracks initiate in the weakest region and the interface is generally the weakest link in concrete. However, in most of the investigations in the literature, the parameters used for characterization of the interface are empirical and experimentally determined [6–9]. Moreover, the parameters evaluated using experimental data are not always consistent and show a wide variability [10].

Some studies have been devoted to the determination of the mechanical properties of the interface between coarse aggregate and mortar. Hsu and Slate [11] found experimentally that the
Study of the Anchorage Connections for Buckling Restrained Braces Part 2: Theoretical Study

Xiao-Kang Guo2,3, Guo-Qiang Li1,2,*, Fei-Fei Sun1,2 and Yu-Shu Liu1,2
1State Key Laboratory for Disaster Reduction in Civil Engineering, Shanghai 200092, China
2College of Civil Engineering, Tongji University, Shanghai 200092, China
3Shanghai Baoye Group Corp., LTD., Shanghai 2000941, China

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Abstract: This paper investigates behaviors of the anchorage connections for buckling restrained braces (BRBs). Finite element (FE) models are established by using software ABAQUS to simulate some tests reported in Part 1 of the companion papers. The material nonlinearities of concrete, anchor bars and anchor plates with the contact property between them are considered in the FE models. A numerical formula is developed for predicting the shear stiffness of anchor bars based on the results from the parametric study using ABAQUS. A formula dealing with the tensile stiffness of the anchor bars is presented relied on the theoretical study. Both of the proposed formulas are verified with the test results. Some design suggestions of the anchorage connections for buckling restrained braces are presented on the basis of the theoretical and experimental studies.

Key word: anchorage connection, buckling restrained brace, theoretical study, finite element method, parametric study, shear and tensile stiffness.

1. INTRODUCTION

In the companion paper Part 1, experimental investigations have been conducted on eight specimens to study the static and hysteretic behaviors of an anchorage connection under mere tension, shear and combined tension and shear, respectively. Some basic working mechanisms of the connection have been revealed from the test results. However, to prompt the connection for practical usage, further studies are required to cover the different design and construction conditions such as layout and yield capacity of the BRBs. Also, to better understand the performance of the connection and to provide more useful design suggestions, additional theoretical analysis is extensively required to examine the applicability of using the anchorage connection for BRBs.

It should be noticed that the anchorage connection is a statically indeterminate system. The primary problem to design the anchorage connection is to determine the distribution of the internal force in the anchor bars. Maheri and Sahebi (1997) reported the use of steel braces in the reinforced concrete frames with four different types of anchorage connections for both retrofitting and new buildings. However, the design details and methods of the connections were not provided in their report.

The recent research on the proposed anchorage connection by the authors shows that eccentric moment will cause the connection fails in an unexpected way, as shown in Figure 1. Although the axis of the BRB passes through the axial cross node O of the beam and column, the connection fails due to rotation caused by the BRB’s tension load. Connection rotation will result in non-uniformly distributed internal force in the anchor bars. Correspondingly, tensile and shear stiffness of the anchor bars should be known to design the anchorage connection.

*Corresponding author. Email address: gqli@tongji.edu.cn; Fax: +86-21-6598-3431; Tel: +86-21-6598-5318.
Prediction of fracture behavior of beam-to-column welded joints using micromechanics damage model

Xuewei Huang, Lewei Tong*, Feng Zhou, Yiyi Chen

State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
Department of Building Engineering, College of Civil Engineering, Tongji University, Shanghai 200092, China

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A B S T R A C T
Moment-resisting steel frames often fail by fracture failure of beam-to-column welded joints during a strong earthquake. This paper provides a numerical methodology based on micromechanics damage model instead of traditional fracture analytical methods to investigate the crack initiation and propagation of welded beam-to-column joints subjected to monotonic loading and ultra low cycle loading conditions. Firstly, parameters used in the micromechanics damage model for steel base metal, heat affected zone and weld metal were calibrated, respectively against uniaxial tension test results and cycle test results of notched specimens. The evolution of void growth in the notched specimens under different loading conditions was compared. Secondly, fracture process of the welded joints subjected to tensile loading was simulated based on the micromechanics damage model. The predicted load displacement response agrees well with the other researcher's test results. Finally, the micromechanics damage model was applied numerically to investigate the ultra low cycle fatigue fracture behavior of the welded joints under constant amplitude as well as variable amplitude inelastic cyclic loading. According to the distribution and evolution of void in the welded joints obtained from finite element analysis, crack initiation and propagation were presented and the number of cycles to fracture was predicted. It is shown that the fatigue life predicted from finite element analysis based on micromechanics damage model agrees well with the other’s test results.

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1. Introduction

Various fractures observed in beam-to-column welded joints during the 1994 Northridge earthquake and 1995 Kobe earthquake, which caused widespread damage to the steel moment-resisting frames, have drawn much attention [1]. Some researches have been carried out to study the ductility of the welded joints subjected to the monotonic tensile loading, and then to access the seismic performances. In these studies, the real beam-to-column welded joint was regularly simplified as a pull-plate specimen [2], and the conventional fracture mechanics methods were adopted, such as the stress intensity factor, crack tip opening displacement (CTOD) and J integral [3–7]. Since they all assumed crack or flaw already existed and there was high strain constraint in the initial crack tip, they were able to predict brittle fracture, but less suitable to the conditions of larger-scale yielding or details without sharp cracks. There are also some other researches on the hysteretic behavior of the welded joints by means of numerous experiments. The seismic performance of the joints was reflected using the energy dissipation capability.

The failure of the structures subjected to cyclic loading resulting from seismic events occurred usually after less than tens of cycles. This fatigue failure, characterized by a few reverse loading cycles (in general less than 20) with large strain amplitude was named as ultra low cycle fatigue (ULCF) [8]. Various approaches have been presented to predict ULCF life of the beam-to-column welded joints. Krawinkler et al. [9], Bernuzzi et al. [10] and Ballio et al. [11] introduced the S–N curve usually adopted in design codes to ULCF analysis, where displacement (or strain) amplitude or rotation amplitude was used instead of stress amplitude. These methods established the relationship between fatigue life and displacement (or rotation) amplitude, but they were not able to predict crack initiation and propagation in the welded joints. According to the theory of fracture mechanics, Krawinkler et al. [9] proposed a power law relation between crack growth rate and plastic strain range based on experimental results. By taking into account the effect of stress triaxiality on the critical plastic strain, Iyama et al. [12] utilized the power law model to study fatigue crack growth behavior of the beam-to-column welded joints. However, the fracture mechanics method is of no use to predict the initiation of a crack. It is only be used to predict crack propagation life from an initial crack which is presumed existing in a structural element.

The micromechanical approach is a powerful methodology for the prediction of crack initiation and growth at the macroscale using characteristics of the microstructure, and then has begun to receive attention in the recent years as a suitable alternative to more traditional...
Vibration control of cables with damped flexible end restraint: Theoretical model and experimental verification

Jian Jiang a,*, Guo-Qiang Li a,b, Yong Lu c

a College of Civil Engineering, Tongji University, Shanghai 200092, China
b State Key Laboratory for Disaster Mitigation in Civil Engineering, Shanghai 200092, China
c Institute for Infrastructure and Environment, School of Engineering, University of Edinburgh, Edinburgh EH9 3JL, UK

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Abstract

This paper presents the theoretical formulation and associated numerical and experimental studies on a novel passive control approach to reducing cable vibrations. In this approach, a damped flexible restraint consisting of a viscous damper and an elastic spring is attached to the end of cable in the horizontal direction to suppress its transverse vibrations. The dynamic equations of the cable-restraint system are established by D'Alembert's principle and then transformed into a set of ordinary differential equations through Galerkin method. These equations are subsequently solved using the Runge-Kutta method. Parametric studies on a prototype cable are performed to investigate the influence of various parameters, particularly the damper coefficient and the spring stiffness, on the suppression of the cable vibrations. A series of laboratory experiments have also been carried out on a 9.5 m scaled cable with the installation of a damped flexible end restraint. The effectiveness of the approach has been verified from the experiments in that a system damping ratio of order of 2% was obtained. The experimental observations are found to be in good agreement with the theoretical predictions.

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1. Introduction

Due to the merits of high strength and lightweight, cables are widely used in structural engineering, marine transportation engineering and power transmission. However, the slenderness of the cables makes them prone to vibration, which may be induced by environmental disturbance such as wind, rain and support movement. Large-amplitude cable vibration is harmful as it accelerates the degradation of the cable structures due to fatigue, and it can also cause discomfort and even anxiety to the observing public.

Cable itself usually has little damping, therefore to suppress the vibration it is necessary to provide external damping and this is traditionally done by attaching transverse dampers at a distance of typically 2%–4% of the span from one of the supports. The effectiveness of transverse dampers can be different for different modes of vibration and it also depends upon pertinent cable parameters such as the sag, bending stiffness and geometric nonlinearity.

A number of studies have been conducted to investigate the damping effect of external viscous dampers in stay cables. Typical results are summarized in Table 1. Kovacs [1] first identified the existence of an optimal size for a transversely...
A simplified approach for fire-resistance design of steel-concrete composite beams

Guo-Qiang Li\textsuperscript{1,2} and Wei-Yong Wang\textsuperscript{3*}

\textsuperscript{1}College of Civil Engineering, Tongji University, Shanghai, 200092, P.R. China
\textsuperscript{2}State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, P.R. China
\textsuperscript{3}College of Civil Engineering, Chongqing University, Chongqing, 400045, P.R. China

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Abstract. In this paper, a simplified approach based on critical temperature for fire resistance design of steel-concrete composite beams is proposed. The method for determining the critical temperature and fire protection of the composite beams is developed on the basis of load-bearing limit state method employed in current Chinese Technical Code for Fire safety of Steel Structure in Buildings. Parameters affecting the critical temperature of the composite beams are analysed. The results show that at a definite load level, section shape of steel beams, material properties, effective width of concrete slab and concrete property model have little influence on the critical temperature of composite beams. However, the fire duration and depth of concrete slab have significant influence on the critical temperature. The critical temperatures for commonly used composite beams, at various depth of concrete and fire duration, are given to provide a reference for engineers. The validity of the practical approach for predicting the critical temperature of the composite beams is conducted by comparing the prediction of a composite beam with the results from some fire design codes and full scale fire resistance tests on the composite beam.

Keywords: steel-concrete composite beam; fire-resistance design; load level; critical temperature

1. Introduction

A steel–concrete composite beam consists of a concrete slab attached to a steel beam by means of shear connectors. The use of steel–concrete composite beams has gained popularity in the last century thanks to its ability to well combine the advantages of both steel and concrete. Composite members exhibit enhanced strength and stiffness when compared to the contribution of their components acting separately, and represent a competitive structural solution in many civil engineering applications, such as bridges and high-rise buildings. However, the steel component in steel-concrete composite beams is sensitive to fire due to the fact that its strength and elastic modules will be reduced quickly when exposed to fire.

Over the last decade, many research papers have been published relevant to the behavior of composite structures in fire. Ranzi et al. (2007a and 2007b) presented a novel numerical model for the analysis of composite steel–concrete beams at elevated temperatures accounting for both

\*Corresponding author, Associate Professor, E-mail: wwyong200@yahoo.com.cn
1. INTRODUCTION

Buckling restrained brace (BRB) is a promising seismic device to protect main frames against earthquakes. BRBs can dissipate a lot of earthquake energy by steel core yielding under both tension and compression without buckling. Till now, BRBs of various configurations have been devised and developed by many researchers (Fujimoto et al. 1988; Iwata et al. 2000; Black et al. 2002). Currently, BRBs are usually applied to steel structures, and the BRBF gusset connection behaviors in steel frames have been systematically studied by Tsai et al. (2012) and Chou et al. (2012). However, few concrete structures have utilized BRBs. One important reason for this situation is that the connections of the BRBs to concrete structures are very complicated. Figure 1 shows a typical steel...
Dynamic Initiation and Propagation of Multiple Cracks in Brittle Materials

Jie Li 1,*, Qiaoping Huang 1,2 and Xiaodan Ren 1

1 Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China; E-Mail: rxdtp@tongji.edu.cn
2 Tongji Architectural Design (Group) Co., Ltd., 1239 Siping Road, Shanghai 200092, China; E-Mail: huangq81@yahoo.com

* Author to whom correspondence should be addressed; E-Mail: lijie@tongji.edu.cn; Tel.: +86-21-6598-3526; Fax: +86-21-6598-0696.

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Abstract: Brittle materials such as rock and ceramic usually exhibit apparent increases of strength and toughness when subjected to dynamic loading. The reasons for this phenomenon are not yet well understood, although a number of hypotheses have been proposed. Based on dynamic fracture mechanics, the present work offers an alternate insight into the dynamic behaviors of brittle materials. Firstly, a single crack subjected to stress wave excitations is investigated to obtain the dynamic crack-tip stress field and the dynamic stress intensity factor. Second, based on the analysis of dynamic stress intensity factor, the fracture initiation sizes and crack size distribution under different loading rates are obtained, and the power law with the exponent of −2/3 is derived to describe the fracture initiation size. Third, with the help of the energy balance concept, the dynamic increase of material strength is directly derived based on the proposed multiple crack evolving criterion. Finally, the model prediction is compared with the dynamic impact experiments, and the model results agree well with the experimentally measured dynamic increasing factor (DIF).

Keywords: brittle materials; dynamic fracture; fragmentation; mechanical properties; strain rate effect; dynamic damage evolution
Modeling and simulation of fluctuating wind speeds using evolutionary phase spectrum

Jie Li,a,b,*, Yongbo Pengb,c, Qi Yan a

a School of Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
b State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China
c Shanghai Institute of Disaster Prevention and Relief, Tongji University, China

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A B S T R A C T

According to the characteristics of vortexes with different frequencies in atmospheric turbulence, a rational hypothesis is proposed in the present paper that the time history of fluctuating wind speeds can be viewed as the integration of a series of harmonic waves with the same initial zero-phase. A univariate model of phase spectrum is then developed which relies upon a single argument associated with the concept of starting-time of phase evolution. The identification procedure of starting-time of phase evolution is detailed and its probabilistic structure is investigated through the estimation of the measured data of wind speeds. The univariate phase spectrum model is proved to be valid, bypassing the need of the classical spectral representation techniques in modeling the phase spectrum where hundreds of variables are required. In conjunction with the Fourier amplitude spectrum, a new simulation scheme, based on the stochastic Fourier functions, for fluctuating wind speeds is developed. Numerical and experimental investigations indicate that the proposed scheme operates the accurate simulation of fluctuating wind speeds efficiently that matches well with the measured data of wind fields by revealing the essential relationship among the individual harmonic waves. The univariate phase spectrum model exhibits the potential application for the accurate analysis and reliability evaluation of random wind-induced responses of engineering structures.

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1. Introduction

The numerical methods used in the computation of wind-induced responses of structures are typically divided into the frequency and time schemes. The frequency scheme has the benefits on computational efficiency in case of analysis of linear structural systems. It is not, however, suitable to the structural systems exhibiting significant nonlinear behaviors, such as the large-span bridges, the high-rising structures and the transmission lines. While the time scheme provides an efficient means for accurately securing the response behaviors of this family of nonlinear structural systems.

The fluctuating wind speeds used in the time scheme is usually simulated by virtue of numerical schemes [7]. The spectral representation method is viewed as one of well-investigated schemes of numerical simulations. It was used to simulate one-dimensional stationary processes of single variable at the beginning of its development in 1950s [13]. In the last half century, the spectral representation method has developed into a comprehensive numerical scheme for simulating the multi-dimensional non-stationary processes of multiple variables [15–17], and received wide applications in the simulation of fluctuating wind speeds [7,18]. The mathematical foundation of the spectral representation method is the superposition of harmonic waves with random phases whereby the stochastic processes can be simulated in accordance with the desirable power spectrum. It is noted that, however, the mathematical foundation of spectral representation methods at least exhibits three challenges [8,10]: (1) The spectral representation method is essentially a simulation scheme towards the second-order moments of stochastic processes where the magnitude of harmonic wave is derived from the objective power spectral density, and the validation of results of the numerical simulation is also carried out using the objective power spectral density by measuring its correlation and the numerical power spectral density. While the probabilistic information included in the simulated stochastic process is not beyond the original second-order moment since the power spectral density belongs to the second-order moment of stochastic process in essence. (2) The spectral representation method encounters the challenges of sample resurgence due to its ensemble properties whereby the components of stochastic processes cannot secure the physical...
STOCHASTIC VISCOS-DAMAGE CONSTITUTIVE MODEL FOR CONCRETE

JIE LI*†‡§ and QIAOPING HUANG*

*School of Civil Engineering, Tongji University
1239 Siping Road, Shanghai 200092, P. R. China
†The State Key Laboratory on Disaster Reduction in Civil Engineering
Tongji University, Shanghai 200092, P. R. China
‡jie@mail.tongji.edu.cn

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A new rate-dependent stochastic damage model for the dynamic modeling of concrete is presented in the paper. This model is formulated on the basis of the stochastic damage model, from which, the static stochastic evolution of damage is strictly derived. Then, rate dependency of concrete is included by means of viscous-damage mechanism. The model predictions are tested against experimental results on concrete specimens that cover different strain rates. The results demonstrate the proposed model may predict dynamic failure behavior of concrete quite well.

Keywords: Concrete; constitutive law; strain rate effect; damage evolution; Stefan effect.

1. Introduction

Concrete and reinforced concrete structures may subject to dynamic loadings during their service period, such as seismic, explosions, and impact. Past studies have shown that concrete exhibits rate-dependent behavior under high strain rate loading, with significant increase of strength and decreasing nonlinearity on the stress–strain curves, when compared to those measured in static tests [Bischoff and Perry, 1991]. Hence a precise constitutive model is needed to properly describe the mechanic behavior of concrete structures for all types of loading.

Up to now, the physical explanation of rate sensitivity of concrete is still under pursuing. Research has shown that, at different loading rates, the strain rate effect may be dominated by different physical mechanisms [Ragueneau and Gatuingt, 2003; Lorefice et al., 2008]. In essential, the strain rate effect of concrete is mainly due to the growth of internal micro-cracking [Ju, 1989; Cervera et al., 1996]. Thus, Ju [1989] proposed a viscous damage mechanism with the regularization structure that is in analogous to that of Perzyna type (1967). Cervera [1996] improved
Experimental investigation of beam-to-tubular column moment connections under column removal scenario

Ling Li b, Wei Wang a,b,⁎, Yiyi Chen a,b, Yong Lu c

a State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
b Department of Building Engineering, Tongji University, Shanghai 200092, China
c Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, UK

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ABSTRACT
Removal of a column member is a typical scenario of local failure that could trigger the progressive collapse of a frame structure. Under such a situation, the behavior of the beam-to-column connection is expected to greatly influence the structural capacity in resisting progressive collapse. This paper presents two full-scale laboratory tests on steel beam-to-tubular column moment connections with outer-diaphragm, one being welded flange-welded web method and the other being welded flange- bolted web method to connect the beam members to the outer-diaphragm, under a column removal scenario. Test results demonstrate that the beam-column assemblies resisted the load applied atop the center column primarily by flexural action in the early stage of the response, and the resistance mechanism gradually shifted towards relying on the catenary action as the vertical displacement increased. Two types of flexural failure modes, namely a continuous flexural failure throughout the section (in the welded-web connection case) and an interrupted flexural failure without the fracture extending upwards (in the bolted-web connection case) were observed from the tests. Two different flexural failure modes dictated the capacity of the respective specimen in developing an effective catenary action in the subsequent phase of the response, and in this respect the bolted-web connection proved to be more redundant in terms of strength and deformability than the welded-web connection.

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1. Introduction
Loss of one or a few load-carrying members is a common initiation event of progressive collapse of a structure. This is well reflected in a typical analysis of a structure against progressive collapse using the widely-adopted alternative load path method [1–4]. Basically, the removal of a structural member triggers a redistribution process of the loads which are originally carried or transferred by the removed member, via other members in the vicinity of the initial damage and possibly involving an extended region. As far as a frame structure is concerned, any individual column may be considered as critical in the paths of the gravity load. Therefore, the removal of a column member becomes the most representative initiation scenario in the analysis of frame structures concerning progressive collapse.

In a column removal scenario, it can be envisaged that the beam-to-column joint region immediately above the removed column will be a key to an effective redistribution of the upper load. The critical role of the behavior of the beam-to-column connection, through the combined axial force and bending moment, in the resistance of the frame against the impending progressive collapse has been discussed extensively in theoretical and analytical studies [5–8] as well as experimental investigations [9–13].

In principle, when an interior column is removed in a moment frame, a double-span mechanism is created and the beam members adjacent to the removed column will tend to resist the gravity load on the double span by the bending moment firstly, i.e., through a flexural action. As the vertical displacement increases because of the flexibility of the doubled span, the deformed beams are elongated due to the axial restraints at the opposite ends of the double-span beams, resulting in axial tension in the beams. Such axial tension in the beams is known as the catenary action and it helps the beams carry the gravity load via the vertical component of the axial tension force, particularly when considerable deflection occurs. The existence of the catenary action, besides the flexural action, has been confirmed by experiments of frame structures where a column removal scenario is simulated, including both reinforced concrete frames [9,10] and steel frames [11–13].

As a matter of fact, the catenary action mechanism will provide the last defense after the flexural action is exhausted or has deteriorated because of flexural failure. The vertical resistance provided by the catenary action depends on two major factors, one being the magnitude of the axial tension generated in the beam members, and another being a sufficient deflection so as to generate a significant
Vibration-based estimation of axial force for a beam member with uncertain boundary conditions

Suzhen Li a,b,*, Edwin Reynders a, Kristof Maes a, Guido De Roeck a

a KU Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, B-3001 Leuven, Belgium
b Tongji University, Department of Building Engineering and the State Key Laboratory of Disaster Research in Civil Engineering, Siping Road 1239, 200092 Shanghai, China

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abstract

Focusing on the application for diagonal braces, tie-bars and short thick cables, this work proposes a new technique to identify the axial force of a two-dimensional Euler–Bernoulli beam member. Bending stiffness effects are taken into account. On the basis of the dynamic measurements from at least five sensors, the proposed method is capable of estimating the axial force as well as the translational and rotational stiffness at both beam ends. When fixing some end constraints, the required number of sensors can be reduced. Finite element simulations are performed for verification purpose, accounting for a wide range of bending stiffness. A laboratory experiment is conducted to investigate the feasibility and accuracy of the proposed method.

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1. Introduction

Axially loaded one-dimensional structural members are widely utilized in civil structures, such as diagonal braces of a truss, cables of a bridge, struts or strings of a space structure and tie-bars for supporting arches or vaults. During the construction and service life of these structures, it is important to accurately and rapidly assess the axial forces of the beam members, whose variation usually presents a critical index to structural degradation and meanwhile affects the internal force distribution in the structure.

Due to convenient excitation devices and reliable measurements, vibration based methods are amongst the most widely employed techniques for in-situ evaluation of the member axial forces. Depending on whether sag-extensibility and bending stiffness are considered or not, these methods may be classified into four categories, including the classic taut string theory that neglects both effects, the approach based on modern cable theory that accounts for sag-extensibility without bending stiffness [1–4], the technique that considers bending stiffness but neglects sag-extensibility [5–7], and the last category that takes the two effects into account [8–12]. For axial force estimation the string theory was first introduced by adopting a simple explicit relation for the measured fundamental frequency. However, as proven by many authors, the ideal assumption of a vibrating wire often leads to unacceptable estimation errors. The second technique mainly focuses on slender or high-tensioned cables. Due to their correspondence with many practical situations, the last two categories that involve bending stiffness effects have attracted extensive attention in recent years. On the basis of single mode natural frequencies, some practical formulas [8,9] are proposed by introducing a nondimensional parameter.
Contribution of U-shaped strips to the flexural capacity of low-strength reinforced concrete beams strengthened with carbon fibre composite sheets

Xiang Li¹, XiangLin Gu²,⁎, XiaoBin Song³, Yu Ouyang⁴, ZhanLei Feng⁵

¹ Department of Building Engineering, Tongji University, Shanghai 200092, China
² Department of Civil Engineering, Shanghai University, Shanghai 200072, China
³ Taikoo Hui (Guangzhou) Development Co. Ltd, Guangzhou 510620, China

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A B S T R A C T

This paper presents the results of an experimental study on the flexural behaviour of low-strength reinforced concrete beams strengthened with externally bonded carbon fibre sheets and on the bond behaviour between these sheets and concrete. The applied sheets without additional anchorage always debonded from the surface of the tested specimens. With the help of U-shaped strips applied at the ends of longitudinal sheets, the load bearing capacity and deforming ability of the strengthened beams could be significantly improved. Based on the fracture mechanics model, the effective shear force between these sheets and concrete was determined. According to the brace-arch model and a further parametric study, it was found that the bearing load of a strengthened beam without additional anchorage increased with the concrete strength and that the calculated capacity of a strengthened beam increased with the sectional area of sheets in a more effective rate when U-shaped strips were applied.

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1. Background

Externally bonded carbon fibre sheets are gradually becoming the preferred method for the structural repair and maintenance of reinforced concrete, due to their characteristics of light weight, high strength, corrosion resistance, and ease of handing on site [1,2]. The structural behaviour of strengthened reinforced concrete (RC) members has been studied in detail [3–5].

Carbon fibre sheets are always externally bonded at the tension side of the beams to improve their flexural capacity. With low-strength concrete, which is defined in this paper as a cubic strength of concrete of less than 15 MPa, it is believed that the existing concrete substrate cannot effectively transfer force to the sheets. Therefore, low-strength concrete beams cannot be strengthened with this method in China [6], which undoubtedly limits the application of this strengthening technology. In most of the historic buildings built at the beginning of the 19th century in Shanghai, the concrete strength is lower than 15 MPa; thus, it is necessary to study the behaviours of beams strengthened with carbon fibre sheets for the preservation of historic constructions and innovation in strengthening technology.

Experimental results have shown that most strengthened concrete beams would fail due to debonding before concrete crushing or fibre rupture [7]. When the length of the sheets was increased, it was found that the ultimate load of the beams strengthened with CFRP sheets of the same sectional area was also increased; however, concrete cover separation was still observed before the calculated bearing load was reached [8]. It has also been reported that even with the CFRP plates extended to the beam supports, the bearing capacities of the strengthened beams were still not improved and concrete cover rip-off was still observed [9]. In order to prevent separation of the concrete cover or delamination of the carbon fibre reinforced polymer (CFRP) sheets, various methods have been investigated. With the help of U-shaped strips [10,11] or a bolted system [12], it has also been found that not only can the flexural capacity of the strengthened beams be increased, but the energy absorption is also improved. However, because the constraint mechanisms are not clearly understood, these additional anchorage systems are always used as construction measures in practice [6]; and, the contribution of the anchorage system cannot be described quantitatively.

Based on test results, Teng and Yao recommended limiting shear force and bending moment together [13]. Mohammad et al. suggested restricting sheet strain to 0.008 [14]; however, even if the effective strains of CFRP are limited, the bearing loads of specimens are still less than the predictions of the guide for strengthening concrete structures (ACI 440) [15].

Since the load bearing capacity of the strengthened beams is determined by the debonding of the CFRP sheets, the bond behaviour is the key point in the contribution of CFRP sheets to the strengthening of low-strength concrete members. In single- or
Experimental Investigation and Design Method Research on Low-Rise Cold-Formed Thin-Walled Steel Framing Buildings

Yuanqi Li¹; Zuyan Shen²; Xingyou Yao³; Rongkui Ma⁴; and Fei Liu⁵

Abstract: Cold-formed thin-walled steel residential building systems, because of their good environment protection, seismic performance, and high construction efficiency, have been widely used in the United States, Canada, Japan, and Australia, and recently, they also have had good application in China. Although a variety of studies have been carried out all over the world in the last 20 years, there is no related design code for this kind of building in China. For this reason, a series of research has been conducted in China recently, considering the consistency of standard systems in structural design in China and the newest development in the world. The contents of the paper can be divided into two parts. First, the major research works conducted by the authors over the last 5 years and the main findings are reviewed and summarized.

Second, based on a Chinese professional standard, a brief summary of the design methods for cold-formed thin-walled steel framing residential buildings developed by the authors and other researchers in China is introduced. DOI: 10.1061/(ASCE)ST.1943-541X.0000720. © 2013 American Society of Civil Engineers.

CE Database subject headings: Cold-formed steel; Steel frames; Buildings; Axial loads; Compression; Eccentric loads; Bending; Connections; Shear walls; Seismic effects.

Author keywords: Cold-formed thin-walled steel framing buildings; Axially loaded compression members; Eccentrically loaded compression members; Bending members; Reliability analysis; Screw connection; Framing shear wall; Seismic performance.

Introduction

Cold-formed thin-walled steel framing building systems were developed in the 1960s, and are mainly used in America, Canada, Japan, and Australia. A wide variety of studies on these systems have been carried out all over the world in the last 20 years. However, these kinds of systems are still in a primary developing phase in China. Because these kinds of systems have some advantages, such as good environment protection, excellent seismic performance, and high construction efficiency, they have been increasingly used in China recently, especially in Shanghai, Beijing, and Shenzhen. Currently, cold-formed thin-walled steel framing buildings are mainly used in residential buildings, in which the number of stories is usually less than 3, the lipped channel sections with S280, S350, and LQ550 steel materials (cold-rolled steel sheets under 2-mm thick with nominal yield strength equal to 280, 350, and 550 MPa, respectively) are used for wall studs, floor joists, and roof trusses, the sheathing materials including gypsum boards, oriented strand boards (OSBs), and corrugated steel sheets are adopted to cover the framing walls, and self-drilling/tapping screws are mainly used in the connections.

GB50018-2002 (Standards China 2002) is the primary code for cold-formed steel structures in effect now in China, which applies to two kinds of steel materials, Q235 and Q345 (generally hot-rolled steel sheets with nominal yield strength equal to 235 and 345 MPa, respectively), and the thickness of the element of main structural members is between 2 and 6 mm. Moreover, the provisions of the code are only for members and connections, not for framing walls and seismic design. Therefore, it is necessary to carry out systematic studies on the design theory and methods to broaden the application area and to accelerate the use of cold-formed thin-walled steel structures in China.

GB50018-2002 (Standards China 2002) adopts an improved effective width method to estimate the load-carrying capacity of cold-formed thin-walled steel sections. The formulas for calculating the effective widths are as follows:

\[
\frac{b_c}{t} = \frac{b_c}{i} + \frac{b}{t} \leq 18\alpha\rho
\]

\[
\frac{b_c}{t} = \left( \frac{21.8\alpha\rho b}{b} - 0.1 \right) \frac{b_c}{i} \quad 18\alpha\rho < \frac{b}{t} < 38\alpha\rho
\]

\[
\frac{b_c}{t} = \frac{25\alpha\rho b_c}{b} + \frac{b}{t} \geq 38\alpha\rho
\]

where \( b, t, \) and \( b_c = \) width, thickness, and effective width of the calculated plates, respectively, as shown in Fig. 1. \( \alpha \) is the adjusting...
A random medium model for simulation of concrete failure

LIANG ShiXue¹, REN XiaoDan¹ & LI Jie¹, 2*

¹School of Civil Engineering, Tongji University, Shanghai 200092, China;
²The State Key Laboratory on Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

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A random medium model is developed to describe damage and failure of concrete. In the first place, to simulate the evolving cracks in a mesoscale, the concrete is randomly discretized as irregular finite elements. Moreover, the cohesive elements are inserted into the adjacency of finite elements as the possible cracking paths. The spatial variation of the material properties is considered using a 2-D random field, and the stochastic harmonic function method is adopted to simulate the sample of the fracture energy random field in the analysis. Then, the simulations of concrete specimens are given to describe the different failure modes of concrete under tension. Finally, based on the simulating results, the probability density distributions of the stress-strain curves are solved by the probability density evolution methods. Thus, the accuracy and efficiency of the proposed model are verified in both the sample level and collection level.

1 Introduction

Concrete, as the most widely used construction material for infrastructures, is featured by its stochastic nonlinearities due to the random distribution of the multiple phases and defects [1]. After years of investigations, two groups of models, i.e., the continuum models based on the continuum damage models and the fracture simulation based discontinuous models, have been proposed to characterize the nonlinear behaviors of concrete.

Within the framework of the continuum damage mechanics, the continuum models [2–5] incline to consider the degeneration of mechanical behaviors by using the continuum damage variable. Based on the definition of the generalized damage variable (avoiding the explicit simulation of cracks and voids), the continuum damage mechanics has its intrinsic advantage to drive the physical mechanisms into the irreversible thermodynamics principles to model a wide range of softening materials, especially the concrete. However, the irreversible thermodynamics only provides a framework for the damage evolution. That is to say, the thermo dynamical inequalities could not define the specified forms of the damage evolution functions, which also play a very important role in continuum damage mechanics. Hence, several empirical expressions of damage evolution were proposed based on the curve fitting of experimental results. In this case, the forms of damage evolution and the corresponding parameters are often lack of physical meanings. What’s more, the generalized damage variable cannot describe the detailed crack propagation and interaction, which are critical to the strength and the failure modes of concrete.

Meanwhile, some researchers turned to the discontinuous models, which tend to simulate the propagation and coalescence of micro-voids and cracks in a direct way. As for a single crack, lying within the infinite homogenous solid, the closed-form solution [6] can be derived based on the classical
Time-dependent analysis of steel-reinforced concrete structures

Jia Lu, Jie Wu*,†, Xiaoqun Luo and Qilin Zhang

College of Civil Engineering, Tongji University, Shanghai, 200092, China

SUMMARY

The time-dependent behavior is a major consideration in the design and construction of tall buildings, especially in concrete and composite structural systems. To make an analysis of long-term effect of steel-reinforced concrete structures, the method of using master–slave constraint to deduce substructure element model of composite members was introduced, and the problem of co-work between steel and concrete was solved. The creep calculation method of combined Age-adjusted Effective Modulus Method (AEMM) and finite element method was adopted. Steel Reinforced Concrete Construction Modeling (SRCCM), a calculation program based on Visual C++ and ObjectARX, was developed for simulating the construction process of high-rise composite structures. The use of the method is illustrated through one computation example of Shanghai Center Tower, which is a super high-rise steel-reinforced concrete structures. The method provides valuable information about time effects that may be used in designing new structures or in diagnosis existing structures. The results also indicate that the vertical shortening of Shanghai Center Tower between column and core-tube is significant. Such differential length changes should be compensated during the construction process of high-rise composite structures. Copyright © 2013 John Wiley & Sons, Ltd.

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KEY WORDS: steel-reinforced concrete structure; construction process; creep; shrinkage; restraint between master and slave nodes; finite element method

1. INTRODUCTION

Composite steel–concrete structures are employed extensively in modern high-rise buildings and bridges. This concept is widespread because it guarantees high strength, full usage of materials, high stiffness and ductility, toughness against seismic loads and significant savings in construction time. Composite structures can be steel-reinforced concrete (SRC) structures or concrete-filled steel tube (CFST) structures. In addition to the aforementioned advantages, SRC structures are gaining popularity due to the higher fire resistance compared with the conventional steel and CFST structures that require additional protection against fire (Dundar et al., 2008; Elllobody and Young, 2011). In China, many in-building or built super high-rise buildings adopted SRC structure, such as the Beijing Shangri-La restaurant, the Shanghai World Financial Center and the Shanghai Center Tower (Figure 1).

In reinforced concrete (RC) buildings, all members are of RC constructions. On the other hand, in SRC structures, some members are RC members, and others are composite members; the behavior of such material is usually time dependent. As a major consequence, stress and strain redistribution is commonly observed, along with a significant increase in deflections and displacements of the structures. Column shortening is a major consideration in the construction of tall buildings (Chowdhary and Sharma, 2011), so the creep and shrinkage of concrete should be taken into account in the construction of SRC structures.

The first observations of concrete shrinkage in the previous century and the discovery concrete creep are in 1907 by Hatt (Bazant, 2001). Some research has been devoted to the calculation method of creep (Fintel and Khan, 1971; Maru et al., 2001). The major approaches to the research of the time-dependent
Evaluation of Shear Strength Design Methodologies for Slender Shear-Critical RC Beams

Zuanfeng Pan\textsuperscript{1} and Bing Li\textsuperscript{2}

Abstract: This paper seeks to examine the concrete contribution to shear strength and determine the inclination of the compressive strut within the variable truss model for slender RC shear-critical beams with stirrups. Using the modified compression field theory in place of the conventional statistical regression of experimental data, the expression for the concrete contribution to shear strength was derived, and the inclination of compressive struts was determined. A simplified explicit expression for shear strength was then provided, with which shear strength can be calculated without extensive iterative computations. This method was then verified using the available experimental data of 209 RC rectangular beams with stirrups and compared with the results obtained through the methods mentioned in ACI 318R-08 (ACI 2008) and CSA-04 (CSA 2004).

Shear Strength for Slender Shear-Critical RC Beams

It is worthwhile to note that for beams with a small \( \lambda \) or deep beams, the hypothesis that plane sections remain plane is not satisfied, and parts of the shear are directly transmitted to the supports by arch action. If the sectional shear design method is used, the results may be conservative without consideration of arch action. For RC beams with stirrups, when \( \lambda \geq 2.5 \), the arch action could be considered small (ASCE-ACI Committee 445 1998). In this paper, the present approach for shear strength based on MCFT is aimed mainly at the slender beams, which means \( \lambda \) of the beam is \( \geq 2.5 \), because the most practical RC beams are slender, with \( \lambda \) ranging from approximately 2.5 to 6 (Kassian 1990; Li and Tran 2008, 2012).

Formulas for shear strength in many codes for RC beams take into account the contribution of concrete \( V_c \) and the contribution of stirrups \( V_s \). The MCFT has made an attempt to simplify the transmitting mechanism of concrete using average stresses, average strains, and local variations (Collins and Mithell 1991). In the theory, the cracked concrete beam must be capable of resisting the effects of the shear, or the beam will fail before the breakdown of the aggregate interlock mechanism, to develop the capacity of a rough and interlocked crack interface for shear transfer. Derived by Collins and Mithell (1991), the contribution of concrete to shear is

\[
V_c = \min \left[ \frac{0.18 \sqrt{f_{cd}} b d_t}{24 \epsilon_1} + \frac{0.3 \epsilon_1 \alpha_1 b d_t \sqrt{f_{cd}} \cot \theta}{1 + \sqrt{500 \epsilon_1}} \right]
\]

From Eq. (1), it can be seen that there are two unknowns needed to calculate shear strength: crack angle \( \theta \) and principal tensile strain \( \epsilon_1 \).

\[
V_c = \frac{0.18 \sqrt{f_{cd}} b d_t}{24 \epsilon_1} + \frac{0.3 \epsilon_1 \alpha_1 b d_t \sqrt{f_{cd}} \cot \theta}{1 + \sqrt{500 \epsilon_1}}
\]

\[V_s = \frac{0.18 \sqrt{f_{cd}} b d_t}{24 \epsilon_1} + \frac{0.3 \epsilon_1 \alpha_1 b d_t \sqrt{f_{cd}} \cot \theta}{1 + \sqrt{500 \epsilon_1}}\]

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Technical Note

Introduction

Although the flexural behavior of RC beams is generally well understood, the explanation of shear mechanisms is relatively inadequate. Over the last century, many researchers have managed to develop semiempirical theories based on extensive experimental data [ASCE-American Concrete Institute (ACI) Committee 426 1973; ASCE-ACI Committee 445 1998]. Representative models include the limit equilibrium theory, the truss model, the strut and tie model, the plastic theory, and the shear friction theory. However, given the complexity of shear failure mechanisms, none of these theories can offer a complete explanation, and as such, there has been no unanimously accepted theory. Recent years have seen renewed efforts to develop a theoretical model that is verified by experimental data. Many truss analogy models such as the traditional 45° truss model, constant or variable angle truss model, and modified compression field theory (MCFT) (Vecchio and Collins 1986) are widely used as the basis of most shear design methodologies for RC beams. The general methods in LRFD-04 (AASHTO 2004) and Canadian Standard-04 (Canadian Standards Association (CSA) 2004) are both based on MCFT. Using the method in AASHTO LRFD-04, for beams with stirrups, the two factors, \( \beta \) and \( \theta \), need to be looked up in the data charts. On the other hand, in CSA-04, it is necessary to determine the longitudinal strain at the middepth of the member using extensive iterative computations and a rough gauge of its initial value. The proposed approach in this paper is based on MCFT, rendering it unnecessary for iterative calculations or reference to data tables.
Experimental observations on 11 RC columns tested at Nanyang Technological University and existing experimental data of 79 shear-critical RC columns are presented. Significant arch action is found in columns with a small shear span-to-depth ratio and high axial-load ratio under shear force. Using the sectional method for shear strength of these types of columns, which does not consider arch action, would give a more conservative prediction. On the basis of the truss-arch model, an expression to predict the shear strength of shear-critical RC columns is presented, which considers both the contributions of concrete and transverse reinforcement to shear strength in the truss model, as well as the contribution of arch action through compatibility of deformation. The proposed model is compared with other shear strength models using the available column test data consisting of 90 shear-critical RC columns, and the results show that the proposed model can improve the accuracy of shear strength predictions for shear-critical RC columns. DOI: 10.1061/(ASCE)ST.1943-541X.0000677, © 2013 American Society of Civil Engineers.

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Author keywords: Shear strength; Reinforced concrete columns; Experimental observation; Truss-arch model; Truss model; Arch action; Shear span-to-depth ratio; Axial-load ratio.

Introduction

A large number of existing RC columns in zones of low to moderate seismicity have not been designed as per the requirements of modern seismic design codes. These are generally termed as nonseismically detailed RC columns. Vital deficiencies in such columns include typical reinforcement details like widely spaced and poorly anchored transverse reinforcements. Recent postearthquake investigations have indicated that these nonseismically detailed RC columns are vulnerable to shear failure, which would drastically reduce their seismic performance and usually lead to structural collapse during earthquakes (Fig. 1). The brittle failure modes, such as shear failure, must be inhibited to satisfy the requirement of seismic response of RC structures. Hence, for existing concrete structures, a thorough evaluation of nonseismically detailed RC columns is needed to mitigate shear failure under earthquake loading, whereas for new concrete structures, the RC columns must be designed with sufficient shear capacity to sustain the whole building in the event of an earthquake. The objective of this paper is to develop a sound model that is capable of predicting the shear strength of shear-critical RC columns.

Over the last century, many researchers have developed sectional models or semiempirical theories on the basis of extensive experimental data to predict the shear strength of RC columns. However, the use of sectional models such as the variable angle truss model or the modified compression field theory (ASCE-American Concrete Institute (ACI) Committee 445 1998) to predict the shear strength fails to consider the arch action in the column and is therefore more conservative. Arch action in RC members subjected to shear force has been recognized by many researchers (Leonardt 1965; Ichinose 1992; Kim et al. 1998). Leonardt (1965) proposed a truss model with inclined compression chords to describe the behavior of arch action in RC beams; in his model, parts of the shear is carried by the inclined compression chord; the rest of the shear is sustained by the web through the truss model. Kim et al. (1998) developed this type of truss-arch model in RC beams and predicted the arch profile and quantified the intensity of arch action by means of the smeared truss idealization technique, as well as experimental investigations on RC beams. On the basis of the experimentally measured steel tensions over the shear span in the RC beams, Kim et al. (1998) proposed an empirical coefficient, α, which represents arch action contribution to total shear capacity. Ichinose (1992) presented a truss-arch model, as shown in Fig. 2, and proposed a design equation to prevent shear failure after flexural inelastic deformation, which has been adopted in the Architectural Institute of Japan (AIJ) Design Guidelines (AIJ 1994). However, in the derivation of the shear design equation (Ichinose 1992) for RC columns, the condition of deformation compatibility between the truss and the arch has not been accounted for, and the height of the strut arch is assumed to be half the height of the column, which does not match the experimental observation. Moreover, in the truss model, the contribution of concrete to shear, such as the aggregate interlock on the crack surface, has not been considered.

This paper presents experimental observations on 90 shear-critical RC columns, of which observations on 11 columns were from tests conducted at Nanyang Technological University (NTU) and another 79 columns were collected from the literature. In this study, a truss-arch model to predict the shear strength of shear-critical RC columns is developed based on the shear strength model of Ichinose (1992). This model can reasonably represent the contributions of shear span-to-depth ratio, αld, and the axial-load.
A UNIVARIATE PHASE SPECTRUM MODEL FOR SIMULATION OF NONSTATIONARY EARTHQUAKE GROUND MOTIONS

YONGBO PENG*† and JIE LI‡§¶

*State Key Laboratory of Disaster Reduction in Civil Engineering
Tongji University, Shanghai 200092, China
†Shanghai Institute of Disaster Prevention and Relief
Tongji University, Shanghai 200092, China
‡School of Civil Engineering, Tongji University
Shanghai 200092, China
§lijie@tongji.edu.cn

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A family of simulation methods for nonstationary earthquake ground motions is proposed. It employs a univariate model of phase spectrum built up on a time argument associated with the concept of starting-time of phase evolution of frequency components. This phase model allows a feasible phase spectrum just using few variables of the starting-time in numerical implementation. In order to reduce the computational effort of the starting-time, a wave-group propagation formulation is also introduced. Two observed ground motions at the type-II site, i.e. Northridge and Chi-Chi waves, are investigated for illustrative purposes. Inspired from the proposed method, a numerical technique for the spatial variation of ground motions is also developed, and the investigation of coherency function between the example ground motions observed at different stations is carried out. Numerical results prove the validity and applicability of the simulation scheme. This methodology provides a new perspective towards the representation of nonstationary stochastic ground motions.

Keywords: Starting-time; wave-group; phase spectrum; ground motions; spatial variation.

1. Introduction

It has been a challenging issue for the accurate modeling of nonstationary earthquake ground motions [Li and An, 2008]. This issue began with the first stationary white-noise ground-motion model for engineering application proposed by Housner in the late of 1940s [Housner, 1947], which made a milestone for the simulation of synthetic ground motions. Accounting for local site properties and a dominant frequency in the ground motion, a family of stationary nonwhite process models were developed [Kanai, 1957; Tajimi, 1960; Housner and Jennings, 1964]. Since

¶Corresponding author.
Multi-scale based fracture and damage analysis of steel fiber reinforced concrete

Xiaodan Ren\textsuperscript{a}, Jie Li\textsuperscript{a,b,*}

\textsuperscript{a}School of Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
\textsuperscript{b}The State Key Laboratory on Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

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\textbf{Abstract}

By adding steel fibers into concrete matrix, the strength and toughness of concrete could be well improved especially for high strength concrete. However, despite numbers of recent works to find out the overall mechanical behaviors of high strength fiber reinforced concrete (FRC), the quantitative assessments of load distribution between reinforcement and matrix and fiber bridging for opening cracks are lacking. Thus the present work concentrates on the high strength fiber reinforced concrete in the view of multi-scale analysis.

A refined numerical model is developed to simulate the behavior of fiber reinforced concrete in meso-level. The steel fibers are modeled by a large number of truss elements which are randomly distributed within the concrete matrix. The concrete are modeled by 3-D solid element. Based on the stress and strain distributions simulated in the meso-level, the homogenized stress and strain in continuum level are resolved by micro-mechanics. And the homogenized damage evolution curve, which is required for the continuum damage model based structural nonlinear analysis, could be calculated based on the multi-scale damage model. The proposed method offers a hierarchical multi-scale framework to investigate the nonlinear behavior of FRC structure in a considerate way.

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1. Introduction

By adding ductile fibers into the brittle matrices, the damage and fracture tolerances of composite materials could be well enhanced. In order to predict the overall properties of the fiber reinforced composites, systematic investigations have been carried out. Among the early works, the shear lag model proposed by Cox [1] was widely adopted to investigate the elasticity and strength of fiber reinforced composites. Within the framework of this model, the load redistribution among fibers were described by the load sharing models, which were extensively studied thereafter. The global load sharing model (GLS) and the local load sharing model (LLS) were proposed by Daniels [2] and Harlow and Phoenix [3] respectively. GLS assumed that the load of a breaking fiber was equally redistributed over all the unbroken fibers, while LLS redistributed the load over the neighborhood fibers around the breaking one, which took into account the stress concentration. The break influence superposition (BIS) technique was proposed by Sastry and Phoenix [4] to analyze the effects of multiple fiber breaks. In recent years, the BIS technique was implemented with finite element method to model the stress transfer from broken to unbroken fibers [5].

In order to model the material toughening induced by fibers, the fracture based models were developed and the concept of crack bridging was stressed. Marshall and Cox [6–8] investigated the fracture of matrix by applying the additional traction induced by the fibers on the crack-tip surfaces. They analyzed the failure modes of the fiber reinforced composites and deter-
A unified dynamic model for concrete considering viscoplasticity and rate-dependent damage

Xiaodan Ren¹ and Jie Li¹,²

Abstract
Precise numerical simulation of structures under dynamic loading is often hampered by the lack of the elaborate rate-dependent nonlinear model of materials. Thus in this article, a unified damage model is proposed to represent the nonlinear behaviors and the rate-dependency of plain concrete in an energy consistent manner. The coupled inviscid plastic damage theory with two damage scalars is first adopted as the multi-dimensional framework of this model. Then based on the strain equivalence hypothesis, the 'effective stress space plasticity' is introduced and its rate-dependent extension is proposed by analogy of the Perzyna-type viscoplasticity. To consider the dynamic damage evolution, the rate-dependent damage evolution is introduced according to the simplified Perzyna-type flow rule. Finally, the unified model is developed by introducing both the 'effective stress space viscoplasticity' and the rate-dependent damage evolution into the elastoplastic damage framework. Under uniaxial tension, the closed form solution of the dynamic increase factor is analytically derived with two material parameters which have been thoroughly investigated in the literatures. The model results also show well agreements with the experimental data in both material and structural levels.

Keywords
Damage, rate-dependency, plasticity, Perzyna model, concrete

Introduction
Concrete is the most widely used material in civil engineering. A tremendous amount of concrete is utilized for construction throughout the world each year. However, the development of concrete science especially concrete mechanics has not been able to meet the demand of design and analysis of...
Experimental Study on Seismic Behavior of Concrete-Filled L-Shaped Steel Tube Columns

Zu-Yan Shen¹,², Min Lei¹, Yuan-Qi Li¹,²,*, Zhen-Yu Lin¹ and Jin-Hui Luo¹

¹Department of Building Engineering, Tongji University, Shanghai 200092, China
²State Key Laboratory of Disaster Reduction in Civil Engineering, Shanghai 200092, China

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Abstract: Concrete-filled L-shaped steel tube columns can be used to save architectural space at room corners, and may have many advantages of structural behavior of common concrete-filled steel tubes as columns. In this paper, the seismic behavior of concrete-filled L-shaped steel tube columns (CFLSTs) was investigated. Six specimens subjected to a constant axial load and cyclically varying lateral loading were tested to study the effects of width to depth ratio of section, depth to thickness ratio of steel tube and axial load level on the strength, as well as stiffness, ductility and energy dissipation of CFLST columns. Experimental results showed that the displacement ductility of CFLST columns decreased significantly with the increase of axial load level, and the strength and stiffness degradations of CFLST columns were more significant with higher axial load level. With the increase of depth-thickness ratio of steel tube and depth-width ratio of section, the ductility and the lateral ultimate load-carrying capacity of CFLST columns also decreased gradually. All CFLST columns exhibited favorable energy dissipation and ductility, even for the columns subjected to high axial load, which indicates that this type of composite columns is adoptable in practical engineering, especially in seismic regions.

Key words: concrete-filled L-shaped steel tube column, cyclic load, ductility, energy dissipation capacity, hysteretic loop, skeleton curve.

1. INTRODUCTION

Concrete-filled steel tube (CFST) columns have been widely used in high-rise buildings, bridges and subway stations in recent decades in many countries due to many advantages, such as high strength and stiffness, favorable ductility, significant fire resistance and convenience of construction. Nevertheless, protrusions of columns at corners in rooms in traditional frame structures may reduce the utilization ratio of area and disturb the aesthetic environment indoors. For saving architectural space and convenient arrangement for furniture, research interest to concrete-filled steel tubes columns with special shapes has been evoked recently, including concrete filled L-shaped, T-shaped and cross-shaped steel tube (CFLST, CFTST, CFCST) columns.

Du et al. (2008) performed axial compression experiments of CFTST stubs. The experimental results indicate that the effect of confinement of steel tube to concrete on carrying capacity of CFTST stubs is considerably small due to the special shape. To postpone the local buckling of steel tube and improve the confinement of steel tube to concrete, some stiffener measures, such as rib stiffeners, bend bars, tensile bars, and indented-shaped reinforcement stiffeners were adopted by researchers. Lin (2009), Chen and Shen (2010) carried out the axial compression experiments of CFLST stubs with or without rib stiffeners. The results show that stiffeners may remarkably improve the ductility of CFLST columns with small depth to width ratio of section, although they cannot effectively
Mechanical Behavior of FRP-Strengthened Concrete Columns Subjected to Concentric and Eccentric Compression Loading

Xiaobin Song, M.ASCE1; Xianglin Gu2; Yupeng Li3; Tao Chen4; and Weiping Zhang5

Abstract: This paper presents the results of a study on the mechanical behavior of concrete columns strengthened with fiber-reinforced polymer (FRP) and subjected to concentric and eccentric compression loading. A numerical analysis model was developed based on the effectively confined concrete area and the stress-strain relationship of the confined concrete established based on compression tests of circular plain concrete columns. The model was verified against the test results of square concentrically loaded plain concrete columns and square eccentrically loaded reinforced concrete columns. An analytical formula of the maximum compression load of square or rectangular fiber reinforced polymer strengthened concrete columns, with respect to the same but nonstrengthened columns, was developed based on the parametric study results by using the verified model. The analytical formula was further verified with the test results of 23 square and rectangular fiber reinforced polymer strengthened columns reported in the literature. Good agreement was achieved. It was found that the increase of the maximum compression load of FRP-strengthened concrete columns, with respect to the same but nonstrengthened columns, increases linearly with the amount of FRP sheets used and decreases linearly with the load eccentricity and exponentially with the concrete compression strength. The last observation implies that the FRP strengthening technique (through wrapping) is most suitable for low-strength concrete buildings. DOI: 10.1061/(ASCE)CC.1943-5614.0000351. © 2013 American Society of Civil Engineers.

CE Database subject headings: Concrete columns; Fiber reinforced materials; Eccentric loads; Compressive strength; Experimentation; Numerical analysis; Compression; Mechanical properties.

Author keywords: Concrete column; FRP strengthening; Concentric compression load; Eccentric compression load; Effectively confined concrete; Maximum compression load.

Introduction

Reinforced concrete (RC) columns may need to be strengthened because of material deterioration and damages caused by accidental overloading, such as earthquakes. Wrapping fiber-reinforced polymer (FRP) sheets around the RC columns has been proven to be effective in improving their strength and ductility because it can provide confinement to the concrete core (Nanni and Bradford 1995). Understanding of the FRP-confining effectiveness and the triaxial state of stresses in confined concrete is essential to the proper strengthening of RC columns through the wrapping of FRP sheets.

There have been continuous research efforts in the compression strength of confined concrete since the 1980s, most of which have been focused on circular concrete columns (Wu and Wang 2009). The confining pressure of FRP wrapping for circular columns is constant and can be determined based on the strength and thickness of the FRP sheets and the diameter of the circular column cross sections. The strength enhancement of FRP-confined concrete can be then evaluated following the work conducted by Richart et al. (1928) for concrete under active hydrostatic pressure. A detailed summary of the existing models for circular FRP-confined columns can be found in Wu and Wang’s work (2009).

There are far fewer studies in the literature on the compression strength of FRP-strengthened square or rectangular columns, where the confinement stress in the FRP sheets is nonuniformly distributed around the perimeter of the concrete cross section, i.e., high at the corners and low near the midpoint of the flat sides. Only the core area (the interior part) of the concrete cross section is effectively confined. The confinement stress is believed to be related to the corner radius and the aspect ratio (width-to-height ratio) of the concrete cross section. Most existing models of the compression strength of confined concrete of square or rectangular cross sections are similar to circular cross sections but with the addition of a shape factor to account for the effect of nonuniform confinement, as summarized by Lam and Teng (2003) and Wu and Wang (2009).

The numerical analysis of FRP-strengthened concrete columns in structural sizes often requires a full description of the mechanical
Stress intensity factors ($K_I$) of cracked non-load-carrying cruciform welded joints repaired with CFRP materials

Tao Chen $^a$, Qian-Qian Yu $^a$, Xiang-Lin Gu $^a$, Guo-Hua Nie $^b$

$^a$ Department of Building Engineering, Tongji University, Shanghai 200092, China
$^b$ School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China

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A B S T R A C T

The adhesively bonded fiber reinforced polymer (FRP) material repair technique has been employed to repair welded joints with defects and extend the fatigue life of welded structures. In this paper, non-load-carrying cruciform welded joints patched with carbon fiber reinforced polymer (CFRP) sheets were studied with the finite element method. A total of 230 cases, where cruciform welded joints were patched with CFRP sheets, were analyzed. Stress intensity factors (SIFs) of mode I ($K_I$) at the crack tip were investigated to evaluate repair performance. It was found that $K_I$ can be significantly reduced by CFRP repairing. The effects of the amount of the repair materials, crack depth and patching sides were also evaluated. The results show that the increase of the elastic modulus of the CFRP and adhesive could significantly decrease the SIF at the crack tip and that the reduction of $K_I$ became more evident with crack depth. Single-sided repairs at the cracked surface were better than double-sided repairs with regard to the surface crack at the weld toe. However, differences between the two repair methods became negligible with increased crack depth.

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1. Introduction

Fatigue damage is one of several reasons for failure in metallic structures subjected to cyclic loading during their service period. Various repair methods have been proposed to extend fatigue life. Recently, strengthening by patching with fiber reinforced polymer (FRP) materials for metallic structures has been shown as a promising rehabilitation method, due to the high stiffness, light weight and high strength of the composites. It has been successfully employed in the aeronautic industry [1,2]. The method has also been introduced to steel or aluminum structures in recent years [3–5].

In addition to costly and time-consuming fatigue tests, theoretical analysis is considered an efficient way to assess fatigue life improvement with regard to repair effects. For metallic structures with defects, fracture mechanics can be adopted; and the stress intensity factor ($K$) can be taken as an essential parameter to analyze crack propagation and fatigue life. To estimate repair performance, $K$ can also be utilized as an important measuring parameter.

Gu et al. carried out finite element (FE) analysis on edge v-notch aluminum plates [6]. They investigated reductions of $K$ and crack opening displacement considering several parameters. Liu et al. investigated the fatigue life of steel plates with a central notch that were repaired with CFRP sheets [7]. They introduced the nominal stress of steel plates and used classical linear elastic fracture mechanics to predict fatigue life, which was integrated with Paris' law. The results revealed that double-sided repairs were better than single-sided repairs for center-cracked plates.

Shen and Hou used an experimental method to obtain $K_s$ for single-sided composite patches [8]. In this and similar studies, the strengthened specimens were designed with a through-the-thickness cut on the edge or at the center [8–11]. This is different from welded joints that have defects and initial cracks on the surface at the weld toe. Limited work has been found for repairing these surface defects in the past decades.

Exploratory experimental results have shown that a composite patch can also retard crack propagation and prolong the life of welded joints at an economical cost [12–14]. In previous work by the authors, fatigue tests were conducted on cruciform welded joints; and the local stress approach was used to assess the fatigue improvement of strengthening with CFRP sheets [13].

The scope of this paper covers an investigation on the stress intensity factors of mode I ($K_I$) in the evaluation of strengthening effects. FE analysis was adopted to obtain $K_I$ of cracked non-load-carrying cruciform welded joints repaired with CFRP materials. The effects of the repair material amounts, modulus, crack depth and repaired sides on the reductions of the $K_I$ were studied.
Stress-Concentration Factors in Circular Hollow Section and Square Hollow Section T-Connections: Experiments, Finite-Element Analysis, and Formulas

L. W. Tong¹; H. Z. Zheng²; F. R. Mashiri, M.ASCE³; and X. L. Zhao, F.ASCE⁴

Abstract: Nodal T-connections made up of circular hollow section (CHS) braces and square hollow section (SHS) chords (CHS-SHS T-connections) have the advantage that they do not require complex brace end preparation when compared with CHS-CHS T-connections. The stress-concentration factors (SCFs) in CHS-SHS T-connections have also been found to be lower than those in SHS-SHS T-connections by previous researchers. At present, no parametric equations have been developed for determination of SCFs for the design of CHS-SHS T-connections. In this investigation, eight CHS-SHS T-connections with unique nondimensional parameters were strain gauged for determination of strain-concentration factors (SNCFs) and therefore SCFs. A three-dimensional finite-element model was then developed using the ANSYS software to simulate the stress distribution at the brace-chord welded interface under axial force and in-plane bending in the brace. Validation of the model was carried out by comparing the SNCFs determined from the experiment and those determined from the finite-element model. It was found that the finite-element models were able to capture both the maximum SNCF in the connection and the SNCF distribution around the brace-chord welded interface. A parametric study was carried out to determine the SCFs for numerous models with unique nondimensional parameters and CHS braces and CHS chords (CHS-CHS T-connections). Because

Introduction

Tubular T-connections made up of circular hollow section (CHS) braces and square hollow section (SHS) chords (CHS-SHS T-connections) have the advantage that they require less complex end preparation compared with nodal T-connections made up of circular hollow section (CHS) braces and CHS chords (CHS-CHS T-connections). Because profiling of the brace is not required in CHS-SHS T-connections, this means that the cost of fabrication and hence construction of these connections is relatively lower. When compared with nodal T-connections made up of square hollow section (SHS) braces and SHS chords (SHS-SHS T-connections), CHS-SHS T-connections have been found to have reduced stress concentrations at the brace-chord welded interface (Bian and Lim 2003; Mashiri et al. 2004). This is so mainly because the change in the brace from a SHS in SHS-SHS T-connections to a CHS in CHS-SHS T-connections results in a reduction in stress concentration factors (SCFs) at the brace weld toes as well as the chord weld toes.

Previous research has been carried out on CHS-SHS T-connections by Bian and Lim (2003), Mashiri and Zhao (2004), Mashiri et al. (2004), Tong et al. (2006), and Packer et al. (2007). This previous research has investigated both the fatigue and static strength of CHS-rectangular hollow section (RHS) T-connections.

Bian and Lim (2003) carried out experimental tests on CHS-RHS T-connections under both static and fatigue loading. Through the measurement of SCFs at hot spot, they concluded that the magnitude of SCFs for CHS-RHS T-connections lies between those of RHS-RHS and CHS-CHS T-connections. Their investigation considered CHS-RHS T-connections under both axial and in-plane bending in the brace.

Research by Mashiri and Zhao (2004) investigated the static strength of CHS-SHS T-connections. Mashiri and Zhao (2004) determined a formula for the static strength of CHS-SHS T-connections made up of thin-walled connections (t < 4 mm) under in-plane bending using plastic mechanism analysis. The formula was based on experimental observation of the chord-face deformation and yield-line analysis.

Study of the seismic response of a recycled aggregate concrete frame structure

Wang Changqing1, 3† and Xiao Jianzhuang1, 2‡

1. Department of Building Engineering, Tongji University, Shanghai 200092, China
2. State Key Lab. for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
3. College of Civil Engineering and Architecture, Nanyang Normal University, Nanyang 473000, China

Abstract: Based on six-degree-of-freedom three-dimensional shaking table tests, the seismic response of a recycled aggregate concrete (RAC) frame was obtained. The analysis results indicate that the maximum story shear force and overturning moment reduce proportionally along the height of the model under the same earthquake wave. The story shear force, base shear coefficient and overturning moment of the structure increase progressively as the acceleration amplitude increases. The base shear coefficient is primarily controlled by the peak ground acceleration (PGA). The relationships between the PGA and the shear coefficient as well as between the PGA and the dynamic amplification factor are obtained by mathematical fitting. The dynamic amplification factor decreases rapidly at the elastic-plastic stage, but decreases slowly with the development of the elastic-plasticity stage. The results show that the RAC frame structure has reasonable deformability when compared with natural aggregate concrete frame structures. The maximum inter-story drift ratios of the RAC frame model under frequent and rare intensity 8 test phases are 1/266 and 1/29, respectively, which are larger than the allowable value of 1/500 and 1/50 according to Chinese seismic design requirements. Nevertheless, the RAC frame structure does not collapse under base excitations with PGAs from 0.066 g up to 1.170 g.

Keywords: recycled aggregate concrete (RAC); frame structure; seismic response; shear coefficient; dynamic amplification factor

1 Introduction

Initially, recycling of building waste was first carried out after the Second World War in Germany (Khalaf and DeVenny, 2004). Since then, a large number of research studies have been carried out to repurpose construction waste as a constituent in new concrete. Previous investigations were mainly engaged in the processing of demolished concrete, mixture design, physical and mechanical properties, and durability improvements. Most of these achievements have been extensively reviewed and summarized by Nixon (1978), Hansen (1986, 1992), ACI555 Report (2002) and Xiao et al. (2006a). It is concluded that some mechanical properties of recycled aggregate concrete (RAC) may, in general, be lower than those of conventional concrete, but it is still sufficient for practical applications in civil engineering.

Many studies on the mechanical behavior and seismic performance of RAC components have been performed in recent years (Xiao et al., 2012a). For example, the shear behavior of RAC beams (Han et al., 2001; Etxeberria et al., 2007; Fathifazl et al., 2010), the flexural performance of RAC beams (Fathifazl et al., 2009), the bearing capacity and deformability of beams and columns made of RAC (Ajdukiewicz and Kliszczewicz, 2007), as well as the seismic behavior of beam-column joints made of RAC under cyclic loading (Corinaldesi and Moriconi, 2006; Xiao et al., 2010) have been investigated and analyzed.

In order to popularize RAC structures, their seismic behavior needs to be investigated. At present, the seismic behavior of plane frame structures made of RAC have been investigated and discussed in the literature. Xiao et al. (2006b) conducted seismic tests of four 1/2 scaled RAC frames under low-frequency cyclic lateral load with constant vertical actions and the test results revealed that the general seismic behavior of RAC frame structures declined as the recycled coarse aggregate (RCA) replacement percentage increased. Min et al. (2011) completed low-cyclic reverse lateral loading tests for two RAC frames with RCA replacement of
Fatigue Behavior of Welded T-Joints with a CHS Brace and CFCHS Chord under Axial Loading in the Brace

Ke Wang1; Le-Wei Tong2; Jun Zhu3; Xiao-Ling Zhao4; and Fidelis R. Mashiri5

Abstract: The welded truss composed of circular hollow section (CHS) braces and concrete-filled circular hollow-section (CFCHS) chords is a new kind of structural system that has been increasingly applied in large span arch bridges in China. It is necessary to have a good knowledge of fatigue strength of the welded CHS-to-CFCHS joints for the design of this kind of composite bridge. This paper reports on a series of tests on welded CHS-to-CFCHS T-joints subjected to axial cyclic fatigue loading in the brace. Eleven joints were designed to investigate various influence factors such as different nondimensional geometric parameters of circular hollow sections and different concrete strength grades. The quality of welds connecting brace and chord members were examined using the magnetic particle and radiographic inspection methods. The conditions of hot spot stress at both the crown and saddle positions in brace and chord members were determined by means of linear and nonlinear extrapolation methods. During the fatigue testing process, the number of cycles relating to several stages of failure, the crack initiation positions, crack propagation patterns, and the final failure modes were recorded. Fatigue strength of the CHS-to-CFCHS T-joints was compared with that of CHS-to-CHS T-joints. It is concluded that the CHS-to-CFCHS T-joints have a much lower stress concentration factor and consequently have better fatigue strength than the CHS-to-CHS T-joints, when both kinds of joints have the same nondimensional geometrical parameters and same nominal stresses on the brace. The \( S_{rh} - N_f \) curves in the Comité International pour le Développement et l’Étude de la Construction Tubulaire guidelines used for CHS-to-CHS joints are not appropriate for the reliable fatigue assessment of CHS-to-CFCHS T-joints based on the current test data. DOI: 10.1061/(ASCE)BE.1943-5592.0000331, © 2013 American Society of Civil Engineers.

CE Database subject headings: Welding; Trusses; Joints; Hollow sections; Stress; Fatigue; Cracking; Axial loads; Bracing.

Author keywords: Welded truss joints; Circular hollow sections; Concrete-filled chords; Hot spot stress; Fatigue tests; Crack initiation and growth; S-N curve.

Introduction

With the increased use of circular hollow sections (CHSs) in the development of infrastructure, concrete-filled circular hollow sections (CFCHSs) have also been used extensively in civil engineering applications. In large span bridges, the arch truss for an arch bridge and the main girders for a cable-stayed bridge can be made of CFCHS chord and CHS brace members. More than 90 arch bridges with the composite tubular trusses have been constructed so far in China (Zhou and Chen 2003). The concrete infill inside chord members may improve the loading capacities of whole truss structures and joints between brace and chord members, as well as provide fire resistance so that the CHS members with a larger ratio of diameter to thickness can be used. Moreover, CHS members filled with concrete or grout are considered as one of most cost-effective and technically sound methods available for the strengthening, modification, and repair of offshore and civil structures [Littlejohn and Hughes 1988; Kibriya and Iqbal 2007; American Bureau of Shipping (ABS) 2004].

When welded connections are used in structures such as cranes, bridges, construction towers, and offshore platforms that are subjected to cyclic loading, the fatigue strength will be one of the key factors to control the life of the structure. Among the several different methods to assess the fatigue behavior of CHS-to-CHS joints, the hot spot stress method establishes a good balance between complexity and accuracy and therefore is much more broadly applicable in many guidelines. Furthermore, the hot spot stress method provides a possibility of estimating the fatigue strength of different types of tubular connections using only the one \( S_{rh} - N_f \) line (van Wingerde et al. 1995).

In the last 30 years, many studies have been carried out on the fatigue behavior of various empty uniplanar and multiplanar tubular joints, leading to parametric formulas to determine their stress concentration factors (SCFs), such as the formulas mentioned in Efthymiou (1998), van Wingerde (1992), Puthli et al. (1989), Zhao et al. (2005), Gao et al. (2007), and Mashiri et al. (2004). The fatigue design approaches for empty welded circular and rectangular hollow section (RHS) joints have been included in the current guidelines of the American Welding Society (AWS) (2008), the American...
Enhancement of ductility of steel moment connections with noncompact beam web

Wei Wang a,b,⁎, Yanyan Zhang b, Yiyi Chen a,b, Zhihao Lu c

a State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
b Department of Building Engineering, Tongji University, Shanghai 200092, China
c Baosteel Engineering & Technology Group Co Ltd., Shanghai 201900, China

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A B S T R A C T

A simple method of welding longitudinal stiffeners (LSs) in the beam web within plastic energy dissipation zone is proposed here to enhance the ductility of beam-to-column connections with noncompact beam web. In this study, a series of cyclic loading experiments on full-scale beam-to-column subassemblies demonstrating weak-beam-strong-panel characteristics, designed using the proposed connection method, were conducted to examine their seismic resistance characteristics. Attention was mainly focused on the ductility and energy dissipation capacity of beams themselves. Test results show that the presence of the LSs is effective in deferring the local buckling of the beam web. The proposed connection method is preferred to enhance ductility of steel moment connections with noncompact beam web in terms of both economic efficiency and fabrication convenience. Parametric studies through simplified finite element models verified by tests were furthermore carried out to clarify the effects of main parameters on the ductility enhancement of steel moment connections. With the increase in the flexural rigidity ratio of the LSs to beam web, the ductility is found to be improved. It is also found that the minimum required flexural rigidity recommended by AASHTO can guarantee good ductility for stiffened connections with the slenderness ratio of beam web less than 130 when sustaining cyclic bending.

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1. Introduction

Deep beams are frequently adopted to provide enough moment resistance in large-span industrial steel building structures subjected to heavy loads. In AISC Specification for Structural Steel Buildings [1], beam sections are classified as compact, noncompact, or slender depending on the slenderness ratio of the web and compression flange. A compact section is one capable of developing a fully plastic stress distribution and possessing significant rotational capacity before the onset of local buckling. A noncompact section is one that can develop a moment equal to or greater than first yield moment before local buckling occurs but cannot develop significant rotational capacity. A slender section is one that fails due to local buckling before the first yield moment is reached. To reduce the weight of the beams, noncompact webs with large depth-to-thickness ratio are often used throughout the beam length, considered as an economical choice for the deep beams. However, the current connection design may be susceptible to significant web buckling in an earthquake. Historically, there has been considerable interest in web buckling, flange buckling, and lateral torsional buckling when evaluating the seismic performance of steel moment-frame connections. Early pre-Northridge connection tests suggested that buckling led to deterioration of the resistance and loss of ductility, because of the concentrated strain that developed in the buckled region. The concerns about local buckling have been changed somewhat by the brittle fractures noted during the Northridge earthquake and by tests performed since the earthquake. However, the previous research [2] have shown that improved performance can be achieved if connections are welded with notch-tough electrodes, if backing bars are removed and weld is backgouged and reinforced, if weld access hole details and web attachments are improved, if there is a good balance of shear and flexural yielding, if lower yield stress steel is employed in the beams, and if the beam depth and span length are kept to appropriate proportions. With these improvements, however, it is possible to achieve the more ductile connection failures, and local buckling issues again become increasingly important to the connection performance.

Some analytical studies were conducted to address the local buckling issue. Nonlinear computer analysis with ABAQUS computer program was used to evaluate how different parameters affect the inelastic stability of moment frames [3]. The web slenderness, flange slenderness, relative lateral support, and the axial restraint were varied for a normal welded flange connection with W30×99 beams and for several comparable reduced beam section (RBS) connections. The analysis suggested that the inelastic behavior was not very sensitive to flange slenderness or the unsupported length, but somewhat greater sensitivity was noted for the web slenderness. Uang and Fan [4] reviewed the results of past RBS experiments, and used regression analysis to estimate trends in behavior. The results of this analysis suggested that web slenderness

⁎ Corresponding author. Tel.: +86 21 65982926; fax: +86 21 65984976.
E-mail address: weiwang@tongji.edu.cn (W. Wang).
Experimental and numerical investigation on full-scale tension-only concentrically braced steel beam-through-frames

Wei Wang a,b,*, Qing Zhou b,d, Yiyi Chen a,b, Lewei Tong a,b, Tak-Ming Chan c

a State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
b Department of Building Engineering, Tongji University, Shanghai 200092, China
c School of Engineering, University of Warwick, Coventry CV4 7AL, United Kingdom
d CITIC General Institute of Architectural Design and Research Co., Ltd., Wuhan 430014, China

Abstract

This paper presents an experimental investigation on two full-scale tension-only concentrically braced beam-through frames (TOCBBFs) with through beam bolted connections. This type of TOCBBF system features cold-formed square-tube section columns connected to H-section through beams by bolted end plate. It is commonly used in low-rise prefabricated buildings. Two two-story, four-span by one-span TOCBBFs subjected to design vertical load were cyclically loaded horizontally to examine the seismic behavior. Stable behavior was observed up to a story drift angle of 1/10. The cyclic behavior was characterized by a linear response, followed by a slip range and a significant hardening response. Deteriorating pinched hysteresis was observed due to the occurrence of cyclic brace compression buckling and tension yielding. The structural damage evolution, ductility, stiffness and shear force distribution of the TOCBBFs were investigated. Moreover, the finite element software ABAQUS was used to investigate the behavior of TOCBBF by nonlinear analysis. Semi-rigid analysis produced the most reasonable prediction including initial lateral stiffness and peak story shear. The calibrated numerical models can be employed to launch further studies for this structural system.

1. Introduction

Concentrically braced frames (CBFs) are recognized as effective structures which provide efficient lateral stiffness and strength [1], and have been commonly used in steel buildings in the regions of high seismic risk during the past 30 years. Compared to steel moment resisting frames (MRFs), CBFs are able to control the lateral displacement and achieve greater lateral strength. A survey of damage to steel buildings was performed shortly after the 1995 Kobe earthquake [2]. The survey showed that of the 452 damaged braced frames, only 29 collapsed (6%) and 141 had severe damage (31%) while 282 (63%) sustained moderate damage or had only minor damage. Due to their favorable performance in reducing the story drift and effective utility of materials, considerable researches have been conducted on the behavior of steel bracing members and on connections and subassemblies from CBFs under earthquake excitations [3,4].

CBFs are expected to accommodate inelastic deformation primarily through ductile tensile yielding and compressive buckling of the braces when subjected to earthquake loading [5]. After compression buckling of steel braces, these members are susceptible to fracture at the mid-span when they are stretched again in tension, which exhibit limited energy dissipation and deterioration of the system stiffness and resistance [6]. In steel braced frames, the energy dissipated through the post-buckling and yielding hysteretic behavior of braces is a significant parameter in determining the seismic behavior of the braced frame [7]. Various factors affect the corresponding hysteretic behavior and the fracture life of the brace during seismic excitations. Experimental and analytical studies have been carried out on those factors including the geometric properties of the brace-gusset assembly such as slenderness ratio and width to thickness ratio of braces [8], brace section shapes as well as gusset plate types [9,10], material properties of braces and the loading patterns [11]. Cyclic tests were carried out on 24 different shapes including double channels, double angles, structural tees, wide-flanges, square and round hollow structural sections. Based on these studies, the effects of the cross section type on the hysteretic behavior were found to be significant.

Tension-only concentrically braced frames (TOCBFs) incorporate very slender bracing members, such as steel rods or flat plates, which are unable to dissipate much energy in compression. A characteristic of TOCBFs is their deteriorating pinched hysteretic behavior during strong earthquakes. A procedure has been proposed to predict the increase in tensile forces at the design stage caused by a yield strength increase of the steel under high strain rate [1]. The TOCBF system, however, continues to be used extensively for low-rise industrial, commercial and residential steel buildings because it is inexpensive and simple to design, prefabricate and erect. Therefore, these structures...
Introduction

The main components of landfill gas (LFG), such as carbon dioxide and methane, are greenhouse gases. Landfills are among the largest anthropogenic sources of methane in the USA. Landfills in the USA emit about one-third of all its emitted methane (Mackie and Cooper, 2009). Landfills emit about 7–20% of all the methane in the atmosphere (Zhang et al., 2004). Although the concentration of methane in the atmosphere is 200 times less than that of carbon dioxide (EI-Fadel et al., 1996), the contribution to global warming of methane has been 23 times more than that of carbon dioxide in the past 100 years (EI-Fadel et al., 1997). Besides, methane in LFG is also a type of volatile gas. When the methane content reaches the explosion limit after transport across the surrounding soil, it will explode upon coming across open fire. In 1983, because of lateral migration of LFG, a house near Loscoe Landfill in Derbyshire exploded after the capping of the landfill. Moreover, in LFG, in addition to carbon dioxide and methane, there is little organic gas. Such gases are called non-methane organic compounds. Although the gross of these gases is small, some are harmful to humans such as xylol and some compounds. People who often come into contact with these gases run the risk of contracting cancer (Zhang, 2008). In addition, the methane in LFG is also a kind of pure energy. According to the research (Wei, 2007), the LFG of Vancouver Landfill contains 200,000,000 GJ of energy, which could provide electric power in Vancouver for 6 years.

Although there are many methods of dealing with municipal solid waste, sanitary landfill is still the main treatment method around the world. Therefore, landfill will exist and increase for a long time. It is necessary to gather and control the LFG to minimize the harm to the environment and the life of LFG. For an efficient gas extraction system design, the rate of gas generation and the spatial gas distribution within a landfill should be known (Garg et al., 2006). The rate of the LFG transport process depends not only on the physical properties of LFG, but also on the characteristics of the landfill space, including the permeability, landfill temperature, moisture, and the type of the surrounding soils. Changes in the atmospheric pressure and temperature can also have a significant effect on LFG migration processes (Hashemi et al., 2002). It is important for the implementation of LFG collection and control to understand gas generation and migration in landfills, as they are essential to minimize the potential hazards associated with LFG generation.

Research on the LFG migration rule usually needs to take into account the leachate collection system, the leachate emission

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Abstract

Landfill gas emissions are recognized as one of the three major concerns in municipal solid waste landfills. There are many factors that affect the generation of landfill gas when the landfill is capped. In this article, a model has been developed based on the theory of porous media flow. The model could predict the pressure distribution of landfill gas in landfill, coupling the effect of landfill settlement. According to the simulation analysis of landfill, it was found that: (a) the landfill gas pressure would reach a peak after 1.5 years, then begin to decline, and the rate of decay would slow down after 10 years; (b) the influence radius of the gas wells is limited; (c) the peak value of landfill gas pressure is larger, it appears later and the rate of decay is slower when the landfill settlement is considered in the model; (d) the calculation of excess gas pressure in landfill under different negative pressures of the extraction well is compared between this model and another model, and the results show that the relative pressure distribution form and range are almost the same.

Keywords

Municipal solid waste, aerogenesis model, settlement of solid waste, gas migration model, landfill gas, decomposition of organic matter

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Numerical simulation of landfill gas pressure distribution in landfills

Yonghui Xi and Hao Xiong

Department of Building Engineering, Tongji University, Shanghai, China

Corresponding author:
Yonghui Xi, Department of Building Engineering, Tongji University, 1239 Siping Road, Yangpu District, Shanghai, 200092, China.
Email: yonghuixi@163.com
Fatigue behavior of recycled aggregate concrete under compression and bending cyclic loadings

Jianzhuang Xiao a,⇑, Hong Li a, Zhenjun Yang b

a Department of Building Engineering, Tongji University, Shanghai 200092, PR China
b School of Mechanical, Aerospace and Civil Engineering, the University of Manchester, Manchester M13 9PL, UK

HIGHLIGHTS

- Fatigue behavior of Recycled Aggregate Concrete was experimentally studied.
- Fatigue strain variation and the fatigue modulus of RAC were analyzed.
- Recycled aggregates have no obvious effects on compressive fatigue behavior.
- Fatigue life of RAC is lower than that of the NAC under cyclic bend loading.

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ABSTRACT

The fatigue behavior of recycled aggregate concrete (RAC) with 100% recycled coarse aggregate (RCA) replacement percentage under uniaxial compression was experimentally investigated in this study. Key quantities, including the residual strain variation, fatigue strain variation and the fatigue modulus of RAC, were calculated and analyzed to correlate the strain response and fatigue damage behavior of RAC. It is found that there exist no obvious differences of compressive fatigue behavior between RAC and natural aggregate concrete (NAC). Based on the experimental results and continuum damage mechanics, a fatigue model relating the fatigue strain variation and the fatigue modulus degradation to the fatigue damage evolution is proposed. Furthermore, RAC with 100% RCA replacement percentage was also tested under cyclic bend loading. It is found that the fatigue life of RAC is lower than that of NAC for the same stress level under cyclic bend loading.

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1. Introduction

Due to the acceleration of urban development, many buildings and structures are being constructed and demolished, resulting in a large amount of waste concrete. For example, over 207 million tons of waste concrete was produced from collapsed buildings and structures caused by a major earthquake in Wenchuan, Sichuan province of China in 2008 [1]. A sustainable and environment-friendly way of disposing of waste concrete is to produce recycle coarse aggregates (RCAs) and then use them to mix recycled aggregate concrete (RAC). It has been used in buildings and road pavements already. However, before the RAC can be widely used in practical engineering structures, sufficient research must be carried out to establish its mechanical properties, safety and reliability under various loading conditions, in comparison with the natural aggregate concrete (NAC).

Reviews [2–7] show that most mechanical properties and durability behavior of RAC are generally inferior to those of NAC. There are two reasons for this. One is that there often exist minor cracks in the recycled coarse aggregates (RCA); another is that there is usually a thin layer of old mortar attached to RCA, resulting in two additional interfaces, one between the coarse aggregates and the old mortar, and another between the old mortar and the new mortar. The above reviews also show that most of the research has been focused on the mechanical behavior of RAC under monotonic static loadings. For example, Xiao et al. [8] obtained the compressive strength and stress–strain curves of RAC with different replacement percentages of RCA by experiments and proposed analytical expressions for the peak strain and the stress–strain relationship. The shear transfer performance across cracks of pre-cracked RAC push-off specimens were also studied by Xiao et al. [9], and it has been found that the shear transfer mechanism and process across cracks in RAC is largely the same as that in NAC, and the RCA replacement ratio adversely affects the shear transfer strength when it is over 30%.
Effects of interfacial transition zones on the stress–strain behavior of modeled recycled aggregate concrete

Jianzhuang Xiao a,⁎, Wengui Li a, David J. Corr b, Surendra P. Shah b

a Department of Building Engineering, Tongji University, Shanghai 200092, PR China
b Center for Advanced Cement-Based Materials, Northwestern University, Evanston, IL 60208, United States

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Based on nanoindentation tests and analysis, the constitutive relationship of the Interfacial Transition Zones (ITZs) in Recycled Aggregate Concrete (RAC) is put forward. Together with the meso/micro-scale mechanical properties of each phase in Modeled Recycled Aggregate Concrete (MRAC), the plastic-damage constitutive models are employed in numerical studies on MRAC under uniaxial compression and uniaxial tension loadings to predict the overall mechanical behavior, particularly the stress–strain relationship. After the calibration and validation with the experimental results, a parametric study has been undertaken to analyze the effects of ITZs and new mortar matrix on the stress–strain relationship of MRAC. It is revealed that the mechanical properties of new mortar matrix and relative mechanical properties between ITZs and mortar matrices play a significant role in the overall stress–strain relationship and failure patterns of MRAC under both uniaxial compression and uniaxial tension loadings.

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1. Introduction

The behaviors of Recycled Aggregate Concrete (RAC) are determined by properties of the waste concrete, the new mix composition, the mixing approach and the deterioration condition of Recycled Coarse Aggregates (RCAs) [1–3]. It is generally accepted that the Interfacial Transition Zones (ITZs), the quality of the old mortar, and the old mortar content of the original concrete influence the properties of RAC. In recent years, RAC has been proven to be commercially and technically sound for both non-structural and structural applications [4–7]. Xiao et al. found that properly designed and constructed RAC frame structures have good load-bearing capacity, deformation and energy dissipation ability to withstand earthquake-type loadings [8].

Quasi-brittle multiphase materials, such as concrete, are widely applied in engineering. Most of them have intrinsic heterogeneous and nonlinear mechanical behaviors due to the random distribution of multiple phases over the nano-, micro-, meso- and macro-scales [9–15]. A better understanding of mechanical properties including the failure processes by both experiments and computer modeling has become one of the most critical research topics for concrete [16–19]. Corr et al. predicted the mechanical properties of concrete in tension with the consideration of meso-scale randomness in the cohesive interface properties [20,21]. Mondal et al. used a nanoindenter along with in-place scanning probe microscopy imaging to determine the nano-scale local mechanical properties of ITZs [22]. Cusatis et al. formulated the Lattice Discrete Particle Model (LDPM) and simulated experiments include uniaxial compression and multiaxial compression, tensile fracture, shear strength, and cyclic compression tests [23,24]. Yip et al. developed an irregular lattice model to simulate the fracture process of multiphase particles, such as concrete [25]. Moreover, concrete was simulated with plastic-damage constitutive model, and showed a very good correlation with the experimental results [26].

To characterize the random heterogeneity in cementitious materials numerically, different phases in the material such as the mortar matrix, aggregates and ITZs can be explicitly modeled by the Finite Element Analysis (FEA), and the material mechanical properties are directly assigned to the elements [27–29]. Al-Rub et al. and Nagai et al. simulated the mortar matrix, coarse aggregate of random shapes and sizes and interfaces in concrete specimens under 2D tensile and compressive loadings [30,31]. Rao et al. used a unit cell approach to model the deformation and failure of single aggregate concrete [32,33]. Xiao et al. numerically simulated the stress distribution characteristics of Recycled Aggregate Concrete (RAC) by commercial FEA software the ABAQUS 6.8 [11]. However, for the previous investigations, the thickness, elastic modulus and strength of ITZs relative to the mortar matrix were not considered during the numerical simulation. Moreover, some numerical simulations even neglected the existence of the ITZs between aggregate and mortar matrix [34].

With the emergence of nanoindentation technology, the properties of the ITZs are available to be measured experimentally [9,22]. Due to the recent advances in understanding the microstructure, thickness, and strength of the ITZ and the developments of computational power, the micromechanical behavior of concrete can be effectively simulated to get a deeper insight into the effect of each phase...
Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation

Jianzhuang Xiaoa,⁎, Wengui Lia,b, Zhihui Sun c, David A. Langed, Surendra P. Shah b

Department of Building Engineering, Tongji University, Shanghai 200092, PR China
bCenter for Advanced Cement-Based Materials, Northwestern University, Evanston, IL 60208, United States
cDepartment of Civil & Environmental Engineering, University of Louisville, Louisville, KY 40292, United States
dDepartment of Civil & Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States

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A B S T R A C T

The properties of new Interfacial Transition Zone (ITZ) and old ITZ in Recycled Aggregate Concrete (RAC) were investigated by Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and nanoindentation. From the SEM images, obvious voids and high concentration of calcium hydroxide can be found in both old ITZ and new ITZ in RAC. Based on the nanoindentation study, it is indicated that the thicknesses of old and new ITZs are in the range 40–50 μm and in the range 55–65 μm, respectively. It is also found that the average indentation modulus of old ITZ is 70–80% of that of old paste matrix, while the average indentation modulus of new ITZ is 80–90% of that of new paste matrix. Additionally, the influences of mix proportion, aggregate types and hydration age on the properties of ITZs in RAC are discussed in this study.

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1. Introduction

Recycling of waste concrete is necessary from the viewpoints of environmental preservation and effective utilization of resources. Recycled Aggregate Concrete (RAC) usually either fully or partially uses crushed and sieved waste concrete as its coarse aggregates [1–4]. Researches based on the comparisons of workability, mechanical properties, and shrinkage and creep with respect to conventional concrete have been published to investigate the early and long-term behaviors of RAC [5–10]. However, very limited studies have been reported to investigate the microstructure of RAC and its effect on the mechanical properties [11,12]. As already known, two types of interfaces exist in RAC: the old Interfacial Transition Zones (ITZs) between adhered old cement mortar and natural aggregates, and the new ITZs between new cement mortar and the aggregates (either recycled aggregates or natural aggregates). This is one of the main differences between RAC and conventional concrete. It is widely accepted that the ITZs in RAC have significant influences on the mechanical properties. Ryu found that the failure behaviors of the RAC depended on the relative quality of old ITZ and new ITZ [13]. The strength of the RAC depends on the quality of new ITZ when the quality of old ITZ is better than that of new ITZ. Otherwise, the strength of RAC depends on the quality of old ITZ. To investigate the effects of the recycling process on recycled aggregate, Nagataki et al. concluded that recycling processing level and quality of the waste concrete played an important role in the characteristics of recycled aggregates [14].

In the past, researchers expressed considerable interests in the micromechanical properties of old and new ITZs in RAC to help understand the complex mechanical behaviors of RAC such as failure mechanism and durability [5,13–15]. However, due to the difficulties in determining constitutive parameters with the available testing methods, the understanding of the fundamental properties of the ITZs in RAC on submicron or nanoscales is still very limited. With the emergence of nanoindentation technology, it is now possible to directly measure the nanomechanical properties of the thin ITZs [16–18]. The nanoindentation technique is similar to classical indentation, but is capable of producing contact areas and penetration depths on submicron or nanoscales for cementious materials [19–22]. In nanoindentation tests, the contact area is measured directly from the depth of penetration of the indenter into the specimen surface and the geometry of the indenter [23,24]. Atomic Force Microscopy (AFM) is another increasingly popular tool for studying cement-based materials [25,26], which is often used to assess concrete surface roughness. In order to study the microstructural gradients of the ITZ in concrete, Scanning
Experimental study on the seismic performance of new sandwich masonry walls

Xiao Jianzhuang1,2†, Pu Jie1‡ and Hu Yongzhong1§

1. Department of Building Engineering, Tongji University, Shanghai 200092, China
2. State Key Laboratory for Disaster Reduction in Civil Eng., Tongji University, Shanghai 200092, China

Abstract: Sandwich masonry walls are widely used as energy-saving panels since the interlayer between the outer leaves can act as an insulation layer. New types of sandwich walls are continually being introduced in research and applications, and due to their unique bond patterns, experimental studies have been performed to investigate their mechanical properties, especially with regard to their seismic performance. In this study, three new types of sandwich masonry wall have been designed, and cyclic lateral loading tests were carried out on five specimens. The results showed that the specimens failed mainly due to slippage along the bottom cracks or the development of diagonal cracks, and the failure patterns were considerably influenced by the aspect ratio. Analysis was undertaken on the seismic response of the new walls, which included ductility, stiffness degradation and energy dissipation capacity, and no obvious difference was observed between the seismic performance of the new walls and traditional walls. Comparisons were made between the experimental results and the calculated results of the shear capacity. It is concluded that the formulas in the two Chinese codes (GB 50011 and GB 50003) are suitable for the calculation of the shear capacity for the new types of walls, and the formula in GB 50011 tends to be more conservative.

Keywords: sandwich wall; seismic performance; shear behavior; cyclic loading test

1 Introduction

Exterior wall is a major component of the envelope of a building. The heat loss through these walls is about 25% of the total heat loss in a building (Zhang and Kou, 2011); in the heated area, this loss is as much as 50% (Qian, 2006). Therefore, insulating the exterior wall is a key technology to achieve energy conservation. Exterior wall insulation is usually achieved by the presence of an insulation layer, and its construction can be classified as internal, external or sandwich according to the relative position between the insulation layer and the wall. Internal insulation does not require much waterproofing, weathering or other technical specifications of decorative and insulation materials; but it considerably reduces the indoor area, and the ring beam, slab and tie column are hotspots for the heat channel (Zhang and Kou, 2011). The influence of the heat channel is mostly eliminated with external insulation, and it protects the structure from its external environment; however, it is easily damaged and is inconvenient to construct and repair (Yang, 2010). Sandwich insulation combines both the advantages of the above two technologies. Therefore, many civil engineers are interested in the development of new types of sandwich walls. However, to the best of the authors’ knowledge, neither the mechanical properties nor the structural behavior of new sandwich walls are well understood. In fact, the seismic response of these new sandwich walls is a safety issue that needs further study.

Sandwich masonry walls, also referred to as multi-leaf masonry walls, have been used since ancient times, and are a typology often found in historical city centers worldwide (Binda et al. 1999, 2001, 2003). A number of experimental investigations have been carried out to study their structural behavior, especially with regard to their compression capacity (Oliveira and Lourenco, 2006; Vintzileou and Tassios, 1995). Binda et al. (2006) proposed a simplified calculation method for the compression capacity. The sandwich insulation wall is accomplished by replacing the rubble material in the interlayer with insulation material, a solution which has been commonly used since the 1930s. In China, sandwich insulation walls have been widely used in heated areas since the late 1980s (Li and Zhou, 2010). Note that in the past, sandwich masonry walls were only used as non-bearing elements. In the 21st century,
Residual compressive and flexural strength of a recycled aggregate concrete following elevated temperatures

A recycled aggregate concrete (RAC) with different replacement percentages of recycled coarse aggregates (RCAs) (i.e., 0, 30, 50, 70, 100 %) was investigated experimentally at elevated temperatures. The residual compressive strength as well as the residual flexural strength of the RAC following elevated temperatures was studied and evaluated. A relationship between the residual compressive flexural strength of RAC and the elevated temperature was proposed. Furthermore, the relationship between the residual flexural strength and the compressive strength of the RAC was compared and analysed. It was found that both the residual compressive strength and the residual flexural strength of the RAC decrease with a rise in temperature, and the effect of the RCAs replacement percentage on the residual flexural strength and the residual compressive strength of RAC was found to be obvious.

Keywords: recycled aggregate concrete (RAC), recycled coarse aggregates (RCAs), residual compressive strength, residual flexural strength, elevated temperature

1 Introduction

Rapid developments in the construction industry have led to a large amount of infrastructure demolition work. This demolition plus the construction of new buildings have produced a great deal of construction and demolition waste. From the viewpoint of environmental conservation and effective utilization of resources, it is beneficial and necessary to recycle the waste concrete. The investigation into recycling waste concrete was initiated in Russia by Gluzhge [1]. Since then, a significant number of studies have been carried out to focus on the recycling of waste concrete in various parts of the world. Previous studies mainly covered the processing of demolished concrete, mix design, mechanical properties and durability aspects [2, 3, 4]. Due to the higher water absorption, higher crushing index and low density of recycled coarse aggregates (RCAs), the mechanical properties and the durability performance of recycled aggregate concrete (RAC) are proved to be degraded compared with those of natural aggregate concrete (NAC). However, only a few investigations have looked at the mechanical behaviour of recycled concrete at elevated temperatures. The research undertaken by Teranishi et al. [5] indicated that the residual compressive strength of RAC was somewhat lower than that of NAC. However, no clear relationship was presented or established between the RCAs replacement percentage and the residual compressive strength. The interesting work completed by Hernández-Olivares and Barluenga [6] shows a reduction in the curvature of the specimens in fire and a higher risk of explosive spalling when high-strength concrete (HSC) is filled and mixed with recycled rubber. But no results were given to express the relationship between the residual mechanical properties and the elevated temperatures after exposure to fire. Terro [7] investigated how replacing fine and coarse aggregates with recycled glass affects the properties of concrete at elevated temperatures.

On the other hand, the fire investigations into normal concrete (NC) [8], lightweight concrete (LWC) [9], high-strength concrete (HSC) [10], high-performance concrete (HPC) [11] and ultra-high-performance concrete (UHPC) [12] have revealed that obvious differences exist regarding the fire behaviour of these different kinds of concrete. In light of this, the fire performance of RAC has to be examined in order to understand fully the properties of this material.

Motivated by the aforementioned facts, an experimental investigation into the fire behaviour of an RAC was carried out and the effect of elevated temperatures on the residual compressive strength and the residual flexural strength of the RAC with different RCAs replacement percentages was analysed. The tests in this investigation were performed at the Advanced Civil Engineering Material Key Laboratory of the Ministry of Education in China at Tongji University.

2 Description of experiments

2.1 Materials

Portland cement conforming to 32.5 R according to Chinese standard GB175-1999 was adopted in this experimental investigation. The fine aggregates used were river sand (siliceous). The siliceous coarse aggregates used were nat-
Simulation Study on the Stress Distribution in Modeled Recycled Aggregate Concrete under Uniaxial Compression

Jianzhuan Xiao; Wengui Li, S.M.ASCE; David J. Corr; and Surendra P. Shah, M.ASCE

Abstract: To investigate the stress distribution in recycled aggregate concrete (RAC) under uniaxial compression, modeled recycled aggregate concrete (MRAC) was studied by numerical simulation. The mechanical properties of interfacial transition zones (ITZs) of RAC were measured by the nanoindentation technique. A two-dimensional numerical study of the stress distribution characteristics of MRAC under the uniaxial compression is presented. The simulation was verified by experimental results. A parametric analysis is then conducted to study the sensitivity of each phase’s mechanical properties and the amounts of old cement mortar in the MRAC. Simulation results demonstrate that a concentration of tensile stress and shear stress appears around new and old ITZ regions. It is found that when the elastic modulus of natural aggregates increases, the magnitude of tensile stress concentration becomes higher, whereas as the elastic modulus of ITZs increases, the magnitude of stress concentration decreases. It is also shown that the higher relative elastic modulus of new cement mortar compared with that of the old cement mortar significantly reduces the stress concentrations at the regions between recycled coarse aggregate particles. The amount of old cement mortar affects the stress distribution in the new ITZ much more obviously than that in the old ITZ. DOI: 10.1061/(ASCE)MT.1943-5533.0000598. © 2013 American Society of Civil Engineers.

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Introduction

Concrete is a complex heterogeneous material, and nonlinear deformation and fracture processes are associated with its progressive failure through initiation, propagation, and coalescence of microcracks. The failure mechanism of concrete at the meso/microlevel is certainly related to the distribution of stresses within the material. Because of the heterogeneity of concrete, the stress distribution in concrete is actually very complex. In the past, several attempts have been made to explain the complex behavior of concrete with the help of testing models. A testing model of concrete, "structural unit," was introduced in studying the behavior of concrete related to microcracking (Shah and Winter 1966). Another idealized concrete model of concrete composed of cement mortar matrix and nine circular discs of aggregates that were embedded in a square array was used to study the strength and deformation behavior of plain concrete subjected to uniaxial and biaxial compressive loads (Buyukozturk et al. 1971). Choi and Shah (1999) prepared one model concrete that contained different numbers of embedded coarse aggregates (1, 5, and 13) to investigate the effect of aggregate spacing on the fundamental fracture process of concrete.

In contrast, a variety of numerical studies on the mechanical properties of cement-based materials have been proposed by several researchers. Ghouse et al. (2010) studied the deformation and failure of concrete using the unit cell model. Schlangen and Van Mier (1992) developed a lattice model with beam elements to simulate the elastic properties of concrete composite by assigning elastic modulus to the corresponding bulk paste matrix. Sun et al. (2007) developed a differential effective medium theory (D-EMT) to compute the elastic properties of concrete composite by assigning elastic modulus to the corresponding bulk paste matrix, interfacial transition zone (ITZ), and aggregate. Corr and Graham applied a moving-window generalized method of cells (GMC) to analyze the effect of spatial randomness in the concrete mesostructure, but the mechanical parameters of the ITZ in concrete were not well understood, and no experimental benchmarks were available to confirm the tests (Corr and Graham 2003; Tregger et al. 2007). Considering two-dimensional elastic models of the cement paste, the aggregate and the ITZ, which is modeled as a thin band around each grain of aggregate, Agioutantis et al. (2000) used the finite-element method (FEM) to calculate the response of the composite material under uniaxial compression. Ramesh et al. (1998) completed a parametric study to investigate the sensitivity of the stress distributions attributable to different aggregate types and changes in the elastic modulus of the transition zone. Abdelmoumen et al. (2010) proposed a numerical concrete model based on the FEM and random unit cell method to calculate the elastic modulus of concrete composites with ITZ. The behavior of the ITZ is directly related to the mechanical performance of the concrete composite.
Wind tunnel test on global drag coefficients of multi-bundled conductors

Qiang Xie, Qigang Sun, Zheng Guan, Yong Zhou

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Multi-bundled conductors of large cross-section are becoming popular due to the increasing application of 1000 kV ultra-high voltage (UHV) transmission lines. However, the aerodynamic characteristics of these conductors have not been investigated systematically, especially the global drag coefficient which is of a vital importance to determine the equivalent static wind load on the conductors. Therefore, a series of wind tunnel experiments were carried out to measure the global drag coefficients of multi-bundled conductors with the conductor diameter, bundle number, wind turbulence intensity and wind attack angles varied. Necessary measures were taken to ensure the accuracy of the test results. The results show that the global drag coefficients vary significantly with the wind attack angles and they decrease with the increase of the conductor diameter and bundle number. In any attack angle, the global drag coefficients of multi-bundled conductors are much smaller than those of a single conductor in the same wind velocity. The biggest global drag coefficients corresponding to different conditions investigated in this study are less than those recommended in the design codes worldwide. This suggests that the global drag coefficient of multi-bundled conductors specified in the current codes can probably be reduced by taking proper consideration of the shielding effect. This will lead to economic benefit in the construction of the UHV transmission lines.

1. Introduction

Wind load is dominant among all the loads exerted on transmission lines and the accurate calculation of its value greatly depends on the drag coefficient recommended in corresponding design codes around the world (GB50545–2010, 2010; ASCE, 2010; British Standard Institution, 1986; Canadian Standards Association, 2003; ESDU, 1980; International Electrotechnical Commission, 2003; JEC–127–1979, 1979). In China, many 1000 kV UHV transmission lines have been constructed or are under construction, in which multi-bundled conductors of large cross-section are widely used. The span between any two adjacent transmission towers is larger in the UHV transmission lines than that in ordinary transmission lines. In fact, the larger the span is, the larger the proportion of the wind loads on the conductors is of the whole loads the towers undertake. So, the amount of the wind force on the tower that can be reduced by taking the shielding effect (the influence of the windward conductors on the leeward ones) into consideration will be larger.

Wardlaw et al. (1975) found that the critical Reynolds number of a single strand conductor was much lower than that of a smooth circular cylinder. In their research, the drag coefficients of a single conductor at different locations in an 8-bundled conductor were measured to investigate the influence of the adjacent conductors. But they did not obtain the global drag coefficient of the multi-bundled conductors or its variation with the wind velocities and wind attack angles. Shan et al. (1992) confirmed the large discrepancy between the drag coefficients obtained from field measurement and from wind tunnel test, which was also reported by (Landers and Palo 1982). To find out the reason leading to the discrepancy, Shan et al. (1992) conducted an experiment to measure the conductor drag coefficient in the open air using a tunnel-like test setup. They found that the drag coefficient measured in this way was in good agreement with that obtained from the wind tunnel test. They believed that the variation of the turbulence and wind pressure along a whole span in the wild wind field caused the discrepancy. Ball et al. (1992) examined the factors that might induce measurement differences in wind tunnel tests, such as the aspect ratio (span/diameter) of conductors and boundary conditions. Storman et al. (1997) positioned the conductors horizontally in the center of a wind tunnel with self-developed end plates and supports to expose them to a better two dimensional flow field so that the adverse effect of the uneven flow field near the wind tunnel wall could be avoided to the greatest extent.

In both the ASCE standard Guidelines for Electrical transmission line structural loading (ASCE, 2010) and the IEC 60826 code Design criteria of overhead transmission lines (International...
Experimental Study on the Mechanical Behavior and Failure Mechanism of a Latticed Steel Transmission Tower

Qiang Xie¹ and Li Sun²

Abstract: Transmission tower collapses caused by strong winds or severe freezing rains frequently occur in many parts around the world. To study the mechanical behavior and failure mechanism of tower structures under such environmental loads, three pairs of tower subassemblies, including one single-panel pair and two double-panel pairs, were designed and statically tested at Tongji University. The difference between the two specimens in each pair was that one had an additional diaphragm as a method of retrofitting while the other did not. One pair of double-panel specimens was tested to simulate and capture the failure pattern of transmission towers subjected to wind load. Correspondingly, two pairs were used to investigate the relevant response of structures under the combination of vertical ice and wind loads. A comparative study on strains at critical sections and local and global deformations as well as failure modes of the tower subassemblies was carried out. The favorable effects of adding the diaphragm, in terms of improving the structural performance of the tower subassemblies, were emphasized in the study. The test results showed that the complex interaction between the main legs and the diagonal bracing members significantly affect the overall stability performance of the towers and their behavior at the ultimate limit state. The study demonstrated that the diaphragms comprehensively improved the mechanical behavior and increased the load-carrying capacity of the transmission tower structures. For specimens subjected to simulated wind load only, the bearing capacity increased by 22.1% after adding horizontal diaphragms. On the other hand, for double- and single-panel specimens subjected to simulated ice and wind loads, the corresponding increases were 17.6 and 18.3%, respectively. The implications of the test results and their relevant practical applications in the wind- and ice-resistant design of transmission towers are summarized and discussed in this paper. DOI: 10.1061/(ASCE)ST.1943-541X.0000722. © 2013 American Society of Civil Engineers.

CE Database subject headings: Steel structures; Towers; Wind loads; Ice loads; Static tests; Diaphragms; Structural failures; Structural stability; Limit states; Electric transmission structures.

Author keywords: Latticed steel tower structure; Wind load; Ice load; Static test; Diaphragm; Failure mechanism; Stability performance; Ultimate limit state.

Introduction

Latticed steel structures are widely used as transmission or telecommunication towers. In most practical applications of this type of structure, steel angles are commonly used because of the ease of connecting them to other structural members (Galambos 1999). However, the mechanical behavior of angles is complex because of the asymmetry of their open cross sections, eccentricities, and diverse restraints. Considerable research efforts have been conducted to study the mechanical properties of steel angles (Chuenmei 1984; Rasmussen 2005; Liu and Hui 2010). A series of standards for the stability of angles at various mechanical states have been established based on those studies [ASCE 1997; European Committee for Standardization (CEN) 2005]. For a typical latticed tower, the primary failure mechanism is the buckling of the main compression members rather than the depletion of the bearing capacity of the tower as a whole. Meanwhile, because the main legs and diagonal braces provide end restraints mutually within the tower structures, they also interact with each other during the whole loading process. These two points indicate the complication of the mechanical behavior of the latticed tower structures.

Natural disasters have been more frequent and severe in the Asia-Pacific region during the past decades. During each disaster, power systems suffered great damage and huge economic losses were consequently caused. In China, in 2005, the gross number of collapsed 500-kV transmission towers caused by severe storms exceeded 18. Similar failure has happened in the United States, Japan, and Australia [Yasui et al. 1999; Savory et al. 2001; Battista et al. 2003; Central Research Institute of the Electric Power Industry (CRIEPI) 2003]. Meanwhile, catastrophic freezing rain also brought severe damage to transmission tower-conductor coupling systems. In early 2008, southern China suffered severe freezing rain and icing disasters. Power transmission systems were subjected to serious failure caused by these ice precipitations. The number of collapsed and damaged towers with ratings above 35 kV of the State Grid Corporation of China, Beijing, and local electrical companies amounted to 7,263 (Xie and Zhu 2011). Consequently, the power system was paralyzed in that area and incredible economic losses were caused. Extreme ice storms also hit many other nations in the world. In January 1998, one severe ice storm struck the Montréal region of Canada. In total, there were about 1,000 transmission tower subassemblies damaged. In addition, as reported by relevant literature, the power systems in many other countries, such as the United States, have experienced serious ice disasters during the past few decades (Henson et al. 2007).
A NEW HIGH-PRECISION BOUNDARY-TYPE MESHLESS METHOD FOR CALCULATION OF MULTIDOMAIN STEADY-STATE HEAT CONDUCTION PROBLEMS

Qiang Xu
Department of Building Engineering, Tongji University, Shanghai, People’s Republic of China

This article presents the idea for calculating 2-D steady-state heat conduction problems with multidomain combination by employing the virtual boundary meshless least-square method. Being different from the conventional virtual boundary-element method (VBEM), this method incorporates the point interpolation method (PIM) with the compactly supported radial basis function (CSRBF) to approximately construct the virtual source function of the VBEM. Thus, the proposed method has the advantages of both the boundary-type meshless method and the virtual boundary element method. Since the configuration of the virtual boundary requires a certain preparation, the integration along the virtual boundary can be carried out over the smooth simple curve that can be structured beforehand (for 2-D problems) to reduce the complexity and difficulty of calculus without loss of accuracy, while the “vertex question” existing in the BEM can be avoided. Numerical examples show that the proposed method is more precise than several other numerical methods while selecting fewer degrees of freedom. In addition, its numerical stability is also verified by computing several cases.

1. INTRODUCTION

The boundary-element method (BEM) is an important kind of numerical method, a semianalytical and seminumerical algorithm. Some scholars solve heat conduction problems by the BEM; e.g., Gao and Wang [1] use the interface integral BEM to solve multimedium heat conduction problems, Ang and Yun [2] employ the complex-variable BEM for axisymmetric heat conduction in a nonhomogeneous solid, Mera et al. [3] solve the one-dimensional backward heat conduction problem by the iterative BEM, Singh and Tanaka [4] adopt a dual-reciprocity boundary element to analyze inverse heat conduction problems, Ochiai and Kitayama [5] analyze three-dimensional unsteady heat conduction by a triple-reciprocity BEM, Ma et al. [6] use the BEM to solve transient heat conduction analysis of 3-D solids with fiber inclusions, and so on. However, these boundary-element methods also have drawbacks, such as that there is a singular integral, its coefficient matrix is a nonsymmetrical full matrix, and it usually takes a long calculation time. Sun et al. presented the virtual boundary-element method (VBEM) to avoid the singular
Experimental research on mechanical behaviors of GFRP bridge decks under alkaline solution

WC Xue and K Fu

Abstract
Glass fiber-reinforced plastic composites are particularly attractive as bridge deck systems due to their high strength, low density, and excellent corrosion resistance, which are of importance to the bridge industry. According to ACI 440.3R–04, the tests consisting of 100 glass fiber-reinforced plastic bridge deck samples were conducted to evaluate the mechanical behaviors of glass fiber-reinforced plastic bridge decks (including tensile property and flexural property) in terms of temperature of the alkaline solution and time period. The parameters of temperature included 40 °C and 60 °C, and the investigated corrosion time included 3.65 days, 18 days, 36.5 days and 92 days, respectively. The micro-formation of the glass fiber-reinforced plastic bridge deck samples surface were surveyed under scanning electron microscopy, which indicated that corrosion pits on the surface of glass fiber-reinforced plastic bridge decks became obvious and the interface between fibers and resins was severely damaged with the aging time and temperature increased. After being exposed to alkaline solution for 92 days at 40 °C and 60 °C, the tensile strength of glass fiber-reinforced plastic bridge decks decreased by 35.43% and 40.58%, respectively, while the flexural strength decreased by 21.36% and 42.10%, respectively. In addition, the degradation model of tensile strength and flexural strength of glass fiber-reinforced plastic bridge deck under alkaline solution were proposed based on Arrhenius equation.

Keywords
Accelerated aging test, glass fiber-reinforced plastic bridge deck, tensile property, flexural property, scanning electron microscope analysis, degradation model

Introduction
Bridge decks are subjected to severe environmental condition and heavy traffic load and sometimes account for a major percentage of a bridge structure’s dead load, hence transportation infrastructure systems deteriorate at an alarming rate in many countries. For example, highway bridge repair each year cost $50 billion in the United States.

In response to the call for more durable bridge construction, a great deal of interest has been given to glass fiber-reinforced plastic (GFRP) composite. GFRP composites offer the advantage of high strength, high fatigue resistance, low density, and better corrosion resistance, which are the desirable characteristics for bridge applications, especially GFRP decks. The existing studies of GFRP bridge deck in China and in other countries related to aspects of design theory, carrying capacity, and production technology, etc., and there is a lack of information about the durability of GFRP bridge decks under alkaline solution. We only find one corresponding literature, which showed that when the GFRP bridge decks were immersed in 23 °C of the alkaline solution for 7 days, tensile strength of GFRP bridge decks decreased by 11.50%.

With the progressive application of GFRP bridge decks in bridge, GFRP bridge decks are in the tensile and flexural state, therefore the research of tensile and...
Time-Dependent Behaviors of Prestressed Concrete Track Girders under Sustained Loads

Weichen Xue*, Ting Liu and Wei Wang
Department of Building Engineering, Tongji University, Shanghai, China

Abstract: Experimental and theoretical studies are conducted to investigate time-dependent behaviors of 4 concrete track girder models (1:5) in rail transit for 1800 days, with an emphasis on effects of types of concrete, stress differences between upper and lower fibers of midspan sections on time-dependent behaviors of prestressed concrete track girders. The test results show that the midspan deflections of the models increase continuously. And smaller time-dependent deflections at midspan are found in the models with HPC or a lower stress difference between the upper and lower fibers of the section at midspan. The theoretical formula based on age-adjusted effective modulus method is proposed to predict time-dependent deflections of prestressed concrete track girders due to creep and shrinkage of concrete and relaxation of prestressed tendons. The deflections at midspan predicted by the formula were compared to the measured values of the girders tested, with close agreement being observed.

Key words: prestressed concrete, track girder, time-dependent behavior, test, theoretical formula.

1. INTRODUCTION
Rail transit is a new public transit system, which has been gaining worldwide popularity due to the advantages of fast speed, comfort, economy, and elegance. To ensure a smooth ride and safety in rail transit system, it is essential that the railway track meets the strict deflection control requirements during its full service life (generally 100 years). The rail transit in the existing field applications primarily consists of ballastless railway track girders, most of which are prestressed concrete girders. For the prestressed concrete girders, time-dependent deflections due to creep and shrinkage of concrete and stress relaxation of prestressed tendons have significant effects on serviceability and safety in rail transit. Therefore, it is necessary to study the time-dependent behaviors of prestressed concrete girders in rail transit.

During the past several decades, much research has been carried out since the first discovery of concrete creep by Hatt in 1907 (Acker et al. 1998). However, the phenomenon of creep is still far from being fully understood, even though it has occupied some of the best minds in the field on concrete research (e.g. McHenry 1943; Neville et al. 1983; Bážant and Panula 1978). At present, various studies on the creep models of concrete have been conducted, which are capable of predicting long-term structural response such as ACI-209 (1992) Model (ACI 209R 1992), CEB-FIP (1990) Model (Muller and Hilsdorf 1990), B3 Model (Bážant and Baweja 2000), GL 2000 Model (Gardner and Lockman 2001), etc. And many test studies (e.g. Patrick 2003; Rodríguez-Gutierrez and Aristizabal-Ochoa 2007; Yang 2005; Abass et al. 2003; Ahlborn et al. 2000; Kelly et al. 2000; Brown et al. 2003; Xue et al. 2011) have been performed on the time-dependent behaviors of prestressed concrete girders, most of which focused on the filed measurement of full-scale prestressed concrete bridge members, but there is still the need for detailed laboratory research into the time-dependent behaviors to complement the test data. And some methods have been

*Corresponding author. Email address: xuewc@tongji.edu.cn; Fax: +86-21-65981216; Tel: +86-21-65981216.
Scheme and application of phase delay spectrum towards spatial stochastic wind fields

Qi Yan¹, Yongbo Peng²,³ and Jie Li *¹,²

¹School of Civil Engineering, Tongji University, Shanghai 200092, China
²State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, China
³Shanghai Institute of Disaster Prevention and Relief, Tongji University, China

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Abstract. A phase delay spectrum model towards the representation of spatial coherence of stochastic wind fields is proposed. Different from the classical coherence functions used in the spectral representation methods, the model is derived from the comprehensive description of coherence of fluctuating wind speeds and from the thorough analysis of physical accounts of random factors affecting phase delay, building up a consistent mapping between the simulated fluctuating wind speeds and the basic random variables. It thus includes complete probabilistic information of spatial stochastic wind fields. This treatment prompts a ready and succinct scheme for the simulation of fluctuating wind speeds, and provides a new perspective to the accurate assessment of dynamic reliability of wind-induced structures. Numerical investigations and comparative studies indicate that the developed model is of rationality and of applicability which matches well with the measured data at spatial points of wind fields, whereby the phase spectra at defined datum mark and objective point are feasibly obtained using the numerical scheme associated with the starting-time of phase evolution. In conjunction with the stochastic Fourier amplitude spectrum that we developed previously, the time history of fluctuating wind speeds at any spatial points of wind fields can be readily simulated.

Keywords: phase delay spectrum; stochastic wind field; spatial coherence; coherence function; wind field simulation; spectral representation method

1. Introduction

The coherence properties of wind fields refer to the statistical relationship between time histories of wind speeds of any two spatial points in frequency domain, which is usually denoted as a coherence function. Panofsky and McCormick first presented the concept of Coherence for wind engineering in 1954 by revealing the conjunctive spectrum and orthometric spectrum of a cross-power spectrum of two segments of wind speed time series (Panofsky and McCormick 1954). The pioneered experimental investigation was carried out by A.G. Davenport, who proposed the celebrated exponential decaying model of coherence function for vertical and horizontal wind fields, respectively, according to the measured data (Davenport 1961, 1967). This model was then
Frame Structural Sizing and Topological Optimization via a Parallel Implementation of a Modified Particle Swarm Algorithm

Bin Yang*, Kai-Uwe Bletzinger**, Qilin Zhang***, and Zhihao Zhou****

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Abstract

As a comparatively new developed stochastic method - Particle Swarm Optimization (PSO), it is widely applied to various kinds of optimization problems especially of nonlinear, non-differentiable or non-concave types. In this paper, a Parallel Modified Guaranteed Converged Particle Swarm algorithm (PMGCPSO) is proposed, which is inspired by the Guaranteed Converged Particle Swarm algorithm (GCPSO) proposed by von den Bergh. Details in the algorithm implementation and properties are presented and, an analytical benchmark test and structural sizing and topological test cases are used to evaluate the performance of the proposed PSO variant, PMGCPSO exhibited competitive performance due to improved global searching ability and its corresponding parallel model indicates nice parallel efficiency.

Keywords: particle swarm optimization, parallel algorithm, frame structures, nonlinear programming, steel structures

1. Introduction

Many scientific, engineering and economic problems involve optimization. In reaction to that, numerous optimization algorithms have been proposed. Clearly, there is an everlasting need to continually improve optimization algorithms with regard to all fields of optimization, simply because the complexity of problems that we attempt to solve is ever increasing. The original particle swarm optimization algorithm was initially proposed in 1995 (Eberhart and Kennedy, 1995). It can be used to solve a wide range of different optimization problems, including most of the problems that can be solved by Evolutionary Algorithms. The PSO is a kind of stochastic algorithm that does not need gradient information derived from the fitness function. This allows the PSO to be used on functions where the gradient is either unavailable or computationally expensive to obtain. Similar to the other evolutionary algorithms, it uses the potential successful particles to search the design space, i.e., every particle has the talent to find the global optimum during the optimization process, even though its current position is the worst one among all of the particles in some iteration.

Generally, the PSO algorithm has the following advantages compared with other optimization algorithms:

(1) It is a simple algorithm with only a few parameters to be adjusted during the optimization process, so that it is easy to be implemented with any modern computer language.

(2) It is a powerful tool, because there is no application limits to it, almost all kinds of optimization problems could be solved by PSO in original forms.

(3) It has a superior convergence speed compared with other evolutionary algorithms, i.e., some optimization problems could be solved efficiently by PSO.

Due to its aforementioned attractive features, it has gained a lot of attentions in recent years. The main works on PSO can roughly be divided into two categories:

(1) Increasing the performance of the PSO, by modifying the original form, combining with other optimization applications, increasing the diversity of the particles, etc.

(2) Expanding the application fields of the PSO, e.g., training neural work, electrics, medicine, power-system management, etc.

Poli (2007) has made a complete search in IEEE Xplore database and achieved a list of about 1100 papers matching the keywords “Particle Swarm Optimization. About 300 of them belong to the improvement of the PSO and the rest belong to the application of the PSO in 26 different categories. Because the IEEE Xplore database focuses on electrical engineering, these categories do not cover the whole application fields of the PSO, some other application fields could be added to this list, e.g., structural optimization in sizing, shape and topology, robust design and etc (Bochenek and Forýš, 2006; Levitin, 2007; Venter, 2004; Prez and Behdinan, 2007; Fourie and Groenwold,
Virtual boundary meshless least square integral method with moving least squares approximation for 2D elastic problem

Dong-Sheng Yang, Qiang Xu*

Department of Building Engineering, Tongji University, Shanghai 200092, China

1. Introduction

The boundary element method (BEM) is an important kind of numerical methods and a semi-analytical and semi-numerical approach. The advantage is the decrease in the dimensionality of the problem and so on. However, BEM has its own drawback, namely the coefficient matrix is asymmetric and the singular integral is produced, when the source point closes to the computational point. Sun et al. presented the virtual boundary element method (VBEM) to solve the singular integral for elasticity [1]. Subsequently, Xu et al. developed the virtual boundary element least square method [2–6]. And the coefficient matrix of the Xu's method is symmetric.

We know that some problems are regarded as single-domain. But slightly complex problem defined as multi-domain need to be calculated by virtual boundary element least square method [7]. With the idea of multi-domain combination, different material combination, such as the problem of inclusions and so on, can be solved.

The meshless method is a hot research topic for recent 20 years. Several interpolation, such as the point interpolation method [8], the radial basis functions [9], the reproducing kernel approximation [10], the partition of unity [11] and the moving least squares approximation [12] (MLSA) and so on are have some advantages or disadvantages. MLSA has been widely used in the meshless method [13–16]. The basis function of the MLSA is simple, and can obtain a solution of high precision. Netuzhylov [14] and Prax et al. [17], Schoenauer and Adolph [18] found that the singularity for MLSA appears, when the data points lie along straight lines. To the authors’ knowledge, the singularity or ill conditioned linear equations set also appears, when the distances between several nodes and calculation point are almost equal. However, sometimes, we do not know that the singularity will appear with the way for the distribution of nodes, a true solution cannot be obtained for an unknown problem by numerical analysis. That is to say, it is important to solve the singularity of the MLSA. So the local weighted orthogonal basis function [19,20] (LWOBF), which is formed from the polynomial basis function by the orthogonalization of Gramm–Schmidt, is employed in this paper.

The meshless method has been extended to the boundary integral equation to form the boundary-type meshless methods. The boundary node method [21], the boundary point interpolation method [22], the boundary radial point interpolation method [23] and the boundary element-free method [19] and the hybrid boundary node method [24] are developed. However, these major boundary-type meshless methods still come across the singular integral, “boundary layer effect” and “vertex question” existing in the BEM. These problems can be solved in VBEM because virtual and real boundaries are not coincidental, the virtual boundary is supposed beforehand and the distance between virtual and real boundaries is considered.

* Corresponding author.

E-mail addresses: 1010020077@tongji.edu.cn (D.-S. Yang), xuqiang@tongji.edu.cn, 1yds415@tongji.edu.cn (Q. Xu).

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Local weighted orthogonal basis function
Elasticity

Moving least squares approximation (MLSA) has been widely used in the meshless method. The singularity should appear in some special arrangements of nodes, such as the data nodes lie along straight lines and the distances between several nodes and calculation point are almost equal. The local weighted orthogonal basis functions (LWOBF) obtained by the orthogonalization of Gramm–Schmidt are employed to take the place of the general polynomial basis functions in MLSA. In this paper, MLSA with LWOBF is introduced into the virtual boundary meshless least square integral method to construct the shape function of the virtual source functions. The calculation format of virtual boundary meshless least square integral method with MLSA is deduced. The Gauss integration is adopted both on the virtual and real boundary elements. Some numerical examples are calculated by the proposed method. The non-singularity of MLSA with LWOBF is verified. The number of nodes constructing the shape function can be less than the number of LWOBF and the accuracy of numerical result varies little.

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On the variability of chloride diffusion in modelled recycled aggregate concrete

Jingwei Ying, Jianzhuang Xiao, Vivian W.Y. Tam

Department of Building Engineering, Tongji University, Shanghai 200092, PR China
School of Computing, Engineering and Mathematics, University of Western Sydney,Locked Bag 1797, Penrith, NSW 2751, Australia

Keywords:
Modelled recycled aggregate concrete (RAC)
Chloride diffusion
Variability
Test
Finite element method (FEM)

Abstract
This paper proposes a new model to describe effects of recycled coarse aggregate (RCA) distribution on chloride diffusion from four modelled recycled aggregate concrete (RAC) with different RCA replacement ratios \(R_{RA}\). Chloride diffusivities of each type of the modelled RAC are experimentally investigated using a rapid chloride migration (RCM) equipment and are simulated by a finite element method (FEM). The results show that the chloride diffusivities of the modelled RAC generally increase with the increase of \(R_{RA}\); while for the same \(R_{RA}\), the chloride diffusivities and the chloride concentration distribution in the modelled RAC are still different due to the effect of different aggregate arrangements; the chloride concentration distribution characteristics in the FEM model are verified using RCM testing; the variability of the modelled RAC for both chloride migration and compressive strength show consistent tendency, which can provide insights into RAC mix design.

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1. Introduction
Concrete variability is one of the essential factors concerning the reliability and service life prediction of reinforcement concrete structures. Previous investigators [1,2] reported that concrete properties obey different probability distributions using statistic methods. For example, the distribution law of concrete porosity and concrete cover thickness are both lognormal with variation coefficients of about 4% and 20% respectively [1]; the distribution law of concrete cover thickness and chloride diffusivity are lognormal and normal respectively [2] with the variation coefficient of about 0.2. In the meso- and micro-scales, concrete can be taken as a composite material consisting of cement paste, voids and aggregate, which are randomly distributed. Therefore, concrete variation is influenced by many factors and its mechanism is difficult to determine.

Recycling concrete is needed from the viewpoints of environmental preservation and sustainable development of the construction industry. In comparison with natural aggregate concrete (NAC), RAC is more porous because of the old cement adhered [3] and its total porosity and average pore diameter increase when the RCA content increases [4]. In addition, the distribution of RCA and natural coarse aggregate (NCA) in space varies with the \(R_{RA}\) as shown in Fig. 1, which may be one of the important factors that influence the RAC properties. Therefore, the variation coefficients of RAC can probably be different from that of NAC. For example, variation coefficient of the compressive strength varies with \(R_{RA}\) of 0%, 30%, 50% and 100% which was recorded from a single source [5]. Xiao et al. [6] found that variation coefficient of RAC derived from different sources is bigger than that from a single source. Additionally, the NAC diffusion coefficient can exhibit a considerable level of variability, which may have variation coefficients between 20% [7] and 40% [8]. As a result, it is more difficult to study the variability of RAC than that of NCA due to the distribution of RCA and NCA in space.

In the past, many researchers have tried to explain the complex mechanical behaviour of concrete using modelled aggregate models. For example, experimental and analytical investigations of simplified concrete models containing nine aggregate types [9] were carried out to study RAC strength and deformation behaviour, subjected to uniaxial compressive stress. Choi and Shah [10] estab-
Five-phase composite sphere model for chloride diffusivity prediction of recycled aggregate concrete

Jingwei Ying
PhD Student, Department of Building Engineering, Tongji University, Shanghai, China; PhD Student, School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia

Jianzhuang Xiao
Professor, Department of Building Engineering, Tongji University, Shanghai, China

Luming Shen
Senior Lecturer, School of Civil Engineering, University of Sydney, Sydney, Australia

Mark A. Bradford
Scientia Professor, Australian Laureate Fellow, School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia

A five-phase composite sphere model for the matrix in recycled aggregate concrete (RAC) is proposed and a closed-form solution for chloride diffusivity is calibrated with available experimental data. Based on a parametric study, it is found that the chloride diffusivity of RAC with Fuller gradation is always smaller than that with an equal volume fraction gradation. Furthermore, the chloride diffusivity of RAC decreases with an increase in minimum aggregate diameter whereas it increases with the old residual mortar content, recycled aggregate replacement rate and thickness of the old interfacial transition zone.

Notation

- $D_{ni}$: chloride diffusivity of new interfacial transition zone (ITZ)
- $D_{nm}$: chloride diffusivity of new mortar
- $D_{oi}$: chloride diffusivity of old ITZ
- $D_{om}$: chloride diffusivity of old mortar
- $d_{\text{max}}$: maximum aggregate diameter
- $d_{\text{min}}$: minimum aggregate diameter
- $h_{0}$: thickness of new ITZ
- $h_{1}$: thickness of old ITZ
- $N_{V}$: number of aggregate particles per unit volume of concrete
- $q_{1}$: $D_{oi}/D_{om}$
- $q_{2}$: $D_{ni}/D_{nm}$
- $R_{\text{RA}	ext{V}}$: volume replacement rate of recycled aggregate (RA)
- $R_{\text{rmv}}$: volume residual rate of old mortar
- $V_{\text{aa}}$: volume fraction of total aggregate
- $V_{\text{na}}$: volume fraction around the new normal aggregate (NA)
- $V_{\text{ai}}$: volume fraction of new ITZ
- $V_{\text{am}}$: volume fraction of new mortar
- $V_{\text{nna}}$: volume fraction of new NA
- $V_{\text{oi}}$: volume fraction of old ITZ
- $V_{\text{om}}$: volume fraction of old mortar
- $V_{\text{ra}}$: volume fraction of RA
- $V_{\text{rai}}$: ITZ volume fraction around the RA
- $V_{\text{roa}}$: ITZ volume fraction of original NA contained in the RA

Introduction

With the global challenge in the twenty-first century of a shortage of natural resources, the recycling of waste concrete is one of the most important means for the implementation of sustainable construction development strategies. However, recycled aggregate concrete (RAC) has a highly complex composition, which leads to significant uncertainties in its properties, use and behaviour. As a result, it is very difficult to evaluate the durability of RAC. Recently, Siddique (2010) studied the effect of municipal solid waste ash on the chloride resistance of concrete. However, the macro-level analysis, ignoring the complicated micro and meso-level structures of concrete, cannot be used effectively to understand the deterioration mechanisms of RAC, which have attracted widespread attention and that will significantly influence the application and popularity of RAC. Normal aggregate concrete (NAC) is usually modelled as a three-phase composite material comprising the aggregates, the cement paste matrix and the interfacial transition zone (ITZ) between the aggregate and cement paste (Zheng and Zhou, 2007). In RAC, the recycled aggregates (RAs) contain old residual mortar, whose properties are usually different from those of new mortar (Juan and Gutierrez, 2009). Moreover, there exists an old ITZ between the old residual mortar and the original aggregate in RAs, and the microstructure of the old ITZ is also different from that of the new ITZ in RAC (Poon et al., 2004). As a result, a realistic model for predicting the physical properties of RAC should take into account the effects of the old residual mortar and the old ITZ, which are the important extra two variables that influence behaviour when compared to normal concrete (Abbas et al., 2009a).
Fatigue behaviour of CFRP strengthened steel plates with different degrees of damage

Q.Q. Yu¹,², T. Chen¹,², X.L. Gu¹,*, X.L. Zhao², Z.G. Xiao³

¹ Department of Building Engineering, Tongji University, Shanghai 200092, China
² Department of Civil Engineering, Monash University, VIC 3800, Australia
³ School of Applied Sciences and Engineering, Monash University, Churchill, VIC 3842, Australia

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Keywords:
Carbon fibre reinforced polymer plate
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Abstract

An experimental and analytical study was conducted to further investigate the effectiveness of the carbon fibre reinforced polymer (CFRP) plates in extending fatigue life of steel structures. Different lengths of artificial cracks were introduced to represent different degrees of fatigue damage. The experimental results demonstrated that the CFRP patches could effectively slow down the crack growth and prolong the fatigue life. A theoretical model was developed to predict the fatigue life of tested specimens. Thereafter, a parametric study was carried out to investigate the fatigue behaviour of steel plates with a wider range of damage degrees. This study extends the understanding of CFRP repair at different stages of crack propagation and provides some useful suggestions for the strengthening method.

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1. Introduction

Fatigue damage is a major concern for many infrastructures such as steel bridges, offshore structures. Repairing and retro-fitting fatigue cracks are more economical and environmentally friendly than replacing the aged steel structures, and are attracting much research attention. Much research has focused on the way of keeping the integrity of steel structures and extending the fatigue life of cracked members. Traditional reinforcement techniques such as the use of stop hole, steel plate attachment and crack plate are either time consuming and costly or complex to apply. Composite fiber patching techniques have been considered as alternatives to these methods of fatigue crack repair in steel structures [1,2], CFRP bonding repair has its own advantage over traditional methods in strengthening work for the outstanding physical and mechanical properties as their high strength, long durability, light weight and ease of installation. The “bonded patch” method was early researched by the Aeronautical and Maritime Research Laboratory in the 1970s [3], and till now, adhesively bonded composite patch repairs have been successfully applied in the aeronautical industry [4–7]. However, research on using CFRP materials to strengthen steel structures in civil engineering is still in the early stage [8]. CFRP materials applied to damaged members can bridge the crack area and transfer the load, thereby decreasing the stress intensity factor (SIF) at the fatigue crack tip and extending the fatigue lives of steel structures. Being different from standard reinforcement, bonding repair neither lessens the cross section due to stop hole nor introduces new stress concentration because of welding. The ease of installation and light weight makes the repair faster to complete without adding much weight. Tavakkolizadeh and Saadatmanesh [9] tested 21 steel beams repaired by CFRP patching. Specimens notched in the tension flange, were reinforced with CFRP plate and loaded in fatigue at different stress levels using a four point bending rig. The fatigue life of retrofitted specimen was greatly extended by 2.6–3.4 times which was equivalent to improve the detail from AASHTO category D to C. Jones and Civjan [10] proposed a series of fatigue experiments on CFRP repaired steel plates. The specimens were either notched from the edge or from a center hole. Variables such as CFRP system, bond length, bond area, one or two sided applications, and applications prior or subsequent to crack propagation were studied. The test results showed that two sided applications extended the fatigue life by as much as 115%. Liu et al. [11,12] presented experimental and numerical studies on center notched steel plates strengthened with CFRP sheets. For double-sided repairs, the repair scheme extended the fatigue life by 2.2–7.9 times compared to the non-strengthened ones. A theoretical model was proposed to predict the crack propagation and fatigue life of the steel plates. High modulus CFRP was adopted in the repair system and it was demonstrated that the strengthening was more effective using CFRP materials with higher modulus [13–15]. The high tensile strength of CFRP allows the application of a pretension to composite strips in order to increase the reinforcement effectiveness. Colombi et al. [16,17], Täljsten et al. [18]...
Triaxial Behavior of Concrete Subjected to Dynamic Compression

Shajie Zeng1; Xiaodan Ren, Ph.D.2; and Jie Li, Ph.D.3

Abstract: Experimental research is presented in this paper to investigate the hydrostatic behavior of concrete under dynamic compression. By using the MTS servohydraulic testing system, strain rates from $10^{-5}$ to $3.5 \times 10^{-2} \text{s}^{-1}$ were achieved. A hydrostatic pressure up to the uniaxial compressive strength of concrete was applied to the specimen with the help of the triaxial loading cell. A series of complete stress-strain curves was obtained for the specimens subjected to different combinations of strain rates and confining pressures, and significant enhancements of the material strength were observed. In particular, the experimental results suggest a clear coupling effect between the enhancements induced by the strain rate and the confining pressures. Finally, a set of empirical formulas is proposed to describe the enhancement of the compressive strength of concrete under different strain rates and relatively low confinement levels. The calculated results agree well with the data of the low confining pressure test and could meet the accuracy requirement in engineering design and applications. DOI: 10.1061/(ASCE)ST.1943-541X.0000686.

CE Database subject headings: Concrete; Strain rates; Stress strain relations; Compression; Triaxial tests.

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Introduction

Knowledge of the behavior of engineering materials under different loading conditions is necessary to support the safe and economical design of structures. For concrete, the full stress-strain curve, which carries thorough information of concrete performance, is often required for the nonlinear analysis of RC structures. Because of the development of stiff testing machines in recent years, the uniaxial test has become a standard tool to investigate the nonlinear material performance. Also, models of the uniaxial stress-strain curve (Simo and Ju 1987; Faria et al. 1998) have been proposed and widely adopted in the nonlinear analysis of RC structures. On the other hand, the multiaxial behavior of concrete, which governs the behavior of concrete elements subjected to shear, torsion, and confinement, has also been investigated by many researchers.

The earliest work for the triaxial test of concrete was reported by Richart et al. (1928). They investigated the failure of concrete under compressive stresses applied in one, in two, or in three directions to study the internal action of the material and the influence of lateral stresses upon the load-carrying capacity of concrete. Since then, the behavior of confined concrete has been studied for several decades (Balmer 1949; Kotsovos and Newman 1978; van Mier 1986a, b; Li and Ansari 1999; Sfer et al. 2002). In particular, van Mier (1985, 1986a, b), since the late 1980s, conducted systematic studies to characterize the multiaxial stress-strain behavior, multiaxial strain softening, postpeak localization, and the effect of concrete size. Based on the test data, van Mier concluded that the physical processes underlying the prepeak and postpeak stress-strain response were basically different and should be treated separately in material models. Later, more experimental data were obtained for the triaxial compression, and a gradual transition from softening to hardening was observed from the experimental tests (Ahmad and Shah 1982; Jamet et al. 1984).

A long-standing interest in the response of concrete subjected to dynamic loads stems from the widespread use of concrete in structures. A reliable constitutive law of concrete material, which requires the support of experimental data under different loading conditions, is crucial for structures analysis (Gran et al. 1989). However, only a few works had been reported on the triaxial behavior of concrete under dynamic loading. Lundeen (1964) performed a series of experiments on the confined cylinders ($d = 38 \text{ mm}$) and observed a $37\%$ increase in the confined strength at a strain rate of $6 \text{s}^{-1}$. In the mid-1980s, a batch of concrete specimens was tested by using three different techniques at different laboratories to investigate the influences of confinement and strain-rate effect. The static tests (Bakhtar et al. 1985) and the unconfined compression tests (Malvern et al. 1985), with strain rates approximately above $10 \text{s}^{-1}$, were performed at Terra Tek Research in Salt Lake City, Utah, and the University of Florida, respectively. The triaxial compression experiments with the strain rates from 1 to $40 \text{s}^{-1}$ were conducted at SRI International in Menlo Park, California (Gran et al. 1985; Gran 1986a, b, 1987). Their triaxial compression data established an approximate shear failure envelope for strain rates between 1.3 and 1.5 $\text{s}^{-1}$, and this envelope was $30\%$ to $40\%$ higher than that for the static loading.

Based on the analysis of the literature, the multiaxial behavior of concrete under dynamic loading needs further investigation. Therefore, the present work presents an experimental investigation of the hydrostatic behavior of concrete subjected to dynamic compression. The hydrostatic tests with the strain rates expected in an earthquake event were achieved by using hydraulic testing machines. Standard cylindrical specimens, 100 mm in diameter and 200 mm in height, were loaded axially with earthquake strain rates in the range of $10^{-5}$ to $3.5 \times 10^{-2} \text{s}^{-1}$ while subjected to constant lateral pressure in...

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1Ph.D. Candidate, School of Civil Engineering, Tongji Univ., Shanghai 200092, China.
2Lecturer, School of Civil Engineering, Tongji Univ., Shanghai 200092, China.
3Distinguished Professor, State Key Laboratory on Disaster Reduction in Civil Engineering, School of Civil Engineering, Tongji Univ., Shanghai 200092, China (corresponding author). E-mail: lijie@tongji.edu.cn
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Cold-formed high strength stainless steel cross-sections in compression considering interaction effects of constituent plate elements

Feng Zhou a,b,⁎, Yiyi Chen a,b, Ben Young c

a State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
b Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
c Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

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A B S T R A C T

This paper presents a numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections in compression. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. The model was then used for an extensive parametric study to investigate the interaction effects of constituent plate elements on Class 3 slenderness limit and section capacities of cold-formed high strength stainless steel square and rectangular hollow sections in compression. The numerical investigation shows that the interaction effects of constituent plate elements on cross-section response are quite obvious particularly for slender sections. The design provisions on Class 3 slenderness limit and effective width equations specified in the EC3 Code and proposed by Gardner and Theofanous are suitable for square hollow sections, but not for rectangular hollow sections since they do not take into consideration of interaction effects of constituent plate element. Hence, the new Class 3 slenderness limit and the section capacity design equations based on the whole cross-section response are proposed in this study, which carefully consider the interaction effects of constituent plate elements.

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1. Introduction

Stainless steel is one of the suitable choices for construction material when durability, long lifespan, easy maintenance and aesthetic appearance are taken into consideration in design. Since the initial cost of structural stainless steel products is approximately four times that of the equivalent carbon steel product [1], hence, the stainless steel structural members must be designed efficiently.

Recently the use of cold-formed stainless steel tubular members in construction is growing rapidly. Many researches have been carried out to study the structural behavior of cold-formed stainless steel tubular members. Experimental and numerical investigations have been performed by Rasmussen and Hancock [2], Young and Hartono [3], Young and Liu [4], Gardner and Nethercott [5] Young and Lui [6], Ellobody and Young [7], Gardner and Theofanous [8], and Theofanous and Gardner [9] on cold-formed stainless steel tubular columns. In most of these investigations, the applicability of the existing stainless steel design provisions on Class 3 slenderness limit and effective width formulae for internal elements in compression as well as the column buckling curve for hollow sections have been assessed.

Design rules for cold-formed stainless steel structural members are available including the ASCE Specification [10] for the Design of Cold-Formed Stainless Steel Structural Members and the EC3 Code [11] Design of Steel structures, Part 1.4: Supplementary Rules for Stainless Steels. The cross-section classification approach is employed in the EC3 Code as a means of codified treatment for local buckling of cross-sections that are partly or fully in compression. However, the interaction of constituent plate elements is not taken into consideration. The EC3 Code treats the plate elements in the cross-section individually, which are classified according to their width-to-thickness ratios as compared to codified slenderness limits. The cross-section response is assumed to the behavior of its most slender plate element in the cross-section. However, the interaction effects of constituent plate elements on cross-section response are obvious regarding the slenderness limits and the cross-section ultimate resistances for cold-formed stainless steel square and rectangular hollow sections subjected to compression [9] and also bending [12]. Both Kato [13] and Beg and Hladnik [14] investigated the interaction effects of constituent plate elements on the local buckling for hot-rolled carbon steel H-sections in bending. Seif and Schafer [15] provided analytical expressions for the elastic cross-section local buckling stress considering plate element interaction effects of hot-rolled steel structural columns.
Web crippling behaviour of cold-formed duplex stainless steel tubular sections at elevated temperatures

Feng Zhou\textsuperscript{a}, Ben Young\textsuperscript{b,}\textsuperscript{*}

\textsuperscript{a}Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
\textsuperscript{b}Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

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Abstract
This paper reports a numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures. Finite element analysis was conducted on cold-formed high strength austenitic and duplex stainless steel material. Four loading conditions specified in the American Specification and Australian/New Zealand Standard for cold-formed stainless steel structures were investigated in the numerical study. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results. It was shown that the finite element model closely predicted the web crippling strengths and failure modes of the tested specimens under the four loading conditions. Hence, parametric study was carried out to investigate the web crippling behaviour of cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures. The web crippling strengths predicted from the finite element analysis were compared with the design strengths obtained using the American, Australian/New Zealand and European specifications for stainless steel structures by substituting the reduced material properties in the current web crippling design equations. A unified web crippling equation for cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures is proposed. It is demonstrated that the web crippling strength obtained using the proposed equation is safe and reliable using reliability analysis.

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1. Introduction

Stainless steels are used in building applications for structural and decorative purpose. For examples, the St Paul’s Cathedral in London and the roof of Chrysler Building in New York. Stainless steel does not only have decorative functions, but it can also provide more durable buildings, better fire resistance and better corrosion resistance. Hence, stainless steel has been increasingly used in structural applications in recent years. Significant progress has been in recent years in the development of design guidance for stainless steel structures in ambient temperature (room temperature). However, investigation of the structural performance of stainless steel structural members at elevated temperatures is relatively limited [1–4].

It is recognised that stainless steel has better structural performance in terms of stiffness and strength than carbon steel at elevated temperatures. Material behaviour of cold-formed stainless steel at elevated temperatures has been reported by Chen and Young [1]. Tensile coupon tests were conducted at different temperatures ranged from approximately 20–1000 °C under both steady and transient state tests. The material properties of stainless steel types EN 1.4462 (Duplex) and EN 1.4301 (AISI 304) were obtained. A unified equation with different coefficients for yield strength, elastic modulus, ultimate strength and ultimate strain of stainless steel at elevated temperatures was proposed based on the test data. The material properties of stainless steel at elevated temperatures have also been conducted [5–8]. The findings of these investigations demonstrated the superior material properties of stainless steel at elevated temperatures, particularly in the temperature ranged approximately from 500 to 800 °C. For example, generally at 800 °C the strength retention of stainless steel is almost 4 times higher than those of carbon steel, and the stiffness retention is 7 times higher than those of carbon steel.

Web crippling is a form of localised buckling that occurs at points of concentrated loads or supports of structural members. Cold-formed stainless steel members that are unstiffened against this type of loading could cause structural failure by web crippling. Cold-formed stainless steel members subjected to web crippling have two different type failure modes. They are web buckling, where the web crippling capacity mainly depends on the stiffness of the material, and web yielding, where the web crippling capacity mainly depends on the yield strength of the material. The current web crippling design rules in most of the specifications for cold-
Experimental and Numerical Investigations of High Strength Steel Welded H-section Columns

Feng Zhou¹, Lewei Tong², and Yiyi Chen²*¹

¹State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, China
²Department of Building Engineering, School of Civil Engineering, Tongji University, Shanghai, 200092, China

Abstract

This paper reports experimental and numerical investigations of high strength steel columns. A series of tests was performed on different geometries of welded H-sections fabricated from high strength steel sheet with a nominal yield stress of 460 MPa. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results of high strength steel welded H-section columns. The calibrated model was shown to provide accurate predictions of the experimental ultimate loads and failure modes of the test specimens. Therefore, a parametric study was carried out over a range of cross-section geometries and column lengths. The test and numerical results of stub columns obtained in this study were compared with the nominal section capacities. It is shown that the design provisions specified in the European Code, American Specification and Chinese Code on yield slenderness limits are all conservative. The normalized flange and web slenderness limits for fully effective section codified in European Code are very close to those codified in the American Specification, which are more suitable. Furthermore, the test and numerical results of long columns obtained in this study were compared with the nominal member capacities predicted using the European Code, American Specification and Chinese Code for steel structures. It is shown that the European Code provides the best agreement between the test and numerical data with design strength predictions for high strength steel welded H-section long columns.

Keywords: Experimental investigation, Finite element analysis, High strength steel, Welded H-section column

1. Introduction

High strength steel is increasingly being used in structural application due to the benefits from the weight saving and reduced fabrication costs of using thin plates (Shi et al., 2008; Miki et al., 2002), however, the scope of the current Chinese Code (2003) for design of steel structures is limited to ordinary steels with nominal yield stress less than 420 MPa. The international European Code (EC3, 2005) for design of steel structures has already extended its rules from ordinary steels to high strength steels with the nominal yield stress up to 460 MPa. In the literature, the structural performance of high strength steel members has been received much attention and a lot of research has been conducted on this topic (Rasmussen and Hancock, 1995; Beg and Hladnik, 1996; Sivakumaran and Yuan, 1998; Gao et al., 2009). The experimental and numerical investigations described in this paper form part of a research program into the strength of members fabricated from high strength steel sheet with a nominal yield stress of 460 MPa, which is recently developed by Baosteel Group Corporation in China. The aim of the research is to investigate whether high strength steel members with such yield stress can be designed according to existing design rules specified in the Chinese Code (2003) or whether these design rules need to be modified to be extended for high strength steel.

The European Code (EC3, 2005) and American Specification (AISC, 2010) employ the concept of cross-section classification for the treatment of local buckling (Topkaya and Şahin, 2011). For the case of pure compression, cross-section failure may occur either by material yielding and inelastic local buckling in the case of stocky cross-sections or by local buckling at an average stress below the yield stress for slender cross-sections (Gardner and Theofanous, 2008). The Chinese Code (2003) also specifies the yield slenderness limits for uniformly compressed plates supported along one or two both longitudinal edges beyond which the section capacity...