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Experimental and numerical studies on lateral torsional buckling of welded Q460GJ structural steel beams

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ABSTRACT

With the development of steel structures, high performance GJ steel has been applied in many large scale projects, such as National Olympic Stadium (Birds Nest), new CCTV Headquarters and Canton Tower in China. In this study, a series of experimental tests and numerical modelling were conducted to investigate the global stability behaviour of Q460GJ structural steel beams. A total of eight doubly symmetric welded beams with lateral restraints at the mid-span were tested under a concentrated load. Finite element analysis (FEA) models considering initial geometric imperfections and residual stresses were also established and verified by experimental results. By using the validated FEA models, parametric studies were carried out as well. The data obtained from parametric studies were compared with the design buckling curves from Chinese steel structure design codes (GB50017-2003, GB50017-201X), American code (ANSI/AISC360-10) and Eurocode 3 (EC3). It was found that the global stability design methods in GB50017-2003 and ANSI/AISC360-10 may not be conservative for GJ structural steel beams with lateral restraints at the mid-span. The design methods in GB50017-201X and EC3 for rolled sections or equivalent welded sections are more appropriate for the overall stability design of GJ structural steel beams.

1. Introduction

With increasing number of large-span and super-high building structures, high performance structural steel, namely GJ structural steel [1] developed by Wuyang Iron and Steel Co. Ltd in China, has been widely used due to its advantages. Similar to high performance steel in Japan [2], GJ structural steel has superior performance, such as lower yield ratio, stable yield stress, better weldability and excellent impact ductility. For instance, high performance Q345GJC structural steel was utilised in the new CCTV Headquarters instead of normal structural steel Q390 to meet the requirements for thick plate field welding. Besides, Q345GJC was also used in National Olympic Stadium (Birds Nest) to satisfy the requirements for seismic design and to reduce the influence of thickness effect. To minimise the structural weight and save construction cost, high performance structural steel Q345GJD, Q420GJD and Q460GJE were used in the project of Phoenix International Media Centre in Beijing when the thickness of steel plates was more than 35 mm. In addition, large-scale projects like Canton Tower, China Petroleum Building, New Capital Airport and National Library, etc. in China have also widely employed GJ structural steel. However, GB/T 19879-2005 [1] only provides specifications for material properties of GJ structural steel, and the applicability of current design methods for GJ structural steel has not been assessed yet. To provide reliable design methods for GJ structural steel members, some studies on GJ structural steel have been carried out. By using sectioning method, Li et al. [3] studied the residual stress distribution of H-sections welded by 80 mm thick GJ structural steel plates. Yang et al. [4] investigated the lateral torsional buckling behaviour of GJ structural steel beams under a concentrated load by experimental tests. However, research studies on structural behaviour of high strength Q460GJ steel members, such as beams, columns and connections, are quite limited to date.

Compared with mild steel, high strength steel has higher yield strength and ultimate strength. Thus, smaller sections can be used to reduce the amount of steel under the same loading conditions, which facilitate transportation and installation. Additionally, using high strength steel can effectively reduce the self-weight of structures, which decreases the seismic actions on structures. Therefore, high strength steel (with nominal yield strength higher than 460 MPa) structures have been increasingly used in many projects,

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such as Shenzhen Bay Sports Centre (Q460D), the National Stadium in China (Q460E/Z35), and CCTV Headquarters (Q460E) in China. High strength steel with nominal yield strength in the range of 460 –690 MPa was used in the Landmark Tower and NTV Tower in Japan, Star City and Latitude Building in Australia as well as Sony Centre in Germany. The load-carrying capacities of steel members are significantly influenced by residual stresses, initial geometric imperfections and material mechanical properties. With increasing steel yield strength, the material elongation and ductility decreases in tension [2]. Significant differences in the stress-strain curve exist between high strength steel and mild steel, and the ratio of residual stress to yield strength also varies with yield strength [5]. High strength steel members have lower sensitivity to initial geometric imperfections than normal strength steel members [6]. Therefore, current design provisions may not be suitable for high strength steel members. Several researchers have carried out studies on 460 MPa high strength steel to verify the applicability of existing design methods. Ban et al. [7,8] and Wang et al. [9,10] investigated the magnitude and distribution of residual stresses in welded H-sections and box sections fabricated by 460 MPa high strength steel. Thereafter, Ban et al. [11] studied the overall buckling behaviour of 460 MPa high strength steel columns by experimental tests and numerical simulations, in which the effect of measured residual stresses on column buckling curves was considered. Six welded H-section columns and six welded box-section columns fabricated by 460 MPa high strength steel were also tested by Wang et al. [12,13] to evaluate the overall buckling behaviour of welded high strength steel columns. Moreover, experimental and numerical investigations on 460 MPa high strength steel welded H-section columns were carried out by conducting six long columns and two stub columns tests by Zhou et al. [14]. 460 MPa high strength steel may be the main structural steel in future building constructions due to its advantages over normal strength steel. However, available studies only focus on the stability behaviour of 460 MPa high strength steel columns, and experimental and numerical results on lateral torsional buckling behaviour of 460 MPa steel beams remain limited.

Till now, researchers have investigated the lateral torsional buckling behaviour of beams fabricated by different materials under different loading conditions. As early as in 1980s, Kubo and Fukumoto [15] conducted experimental tests on thin-walled I-shaped beams, of which the yield stress ranged from 262 to 316 MPa. Thereafter, experimental and theoretical studies on the behaviour of high strength steel flexural members were carried out by researchers in the United States and Japan. Kuwamura [16] and Kato [17,18] analysed the effects of high strength steel with high yield ratio, no apparent yield plateau and low elongation on the mechanical properties of flexural members. Based on existing work, Trahair [19] pointed out the research need in buckling of steel beams of different types of material and cross section. Sause and Fahnestock [20] carried out the three-point bending tests on 690 MPa high-performance steel flexural members and compared the test result with that of mild steel. Green [21] conducted experimental and analytical studies on the effects of several parameters on the strength and ductility of high-performance steel flexural members with 550 MPa yield stress. Experimental and analytical results indicated that rotational capacities of high-strength steel members decrease with increasing web and compression flange slenderness and were affected by material stress-strain characteristics. Liu and Gannon [22] designed a special four-point loading system to investigate the stability performance of strengthened steel beams. In addition, the behaviour of steel beams with lateral restraints have also been investigated by some researchers. Chen [23] investigated the influence of end restraints in the beam plane and intermediate lateral restraints on the overall stability of beams. Foster and Gardner [24] conducted twelve four-point bending tests on beams with discrete rigid and elastic lateral restraints and numerical analyses to investigate the implications of utilizing strain-hardening in the design of restrained members on bracing forces and stiffness requirements. McCann et al. [25] investigated the design methods for steel beams with discrete lateral restraints and one method has been developed to optimise the design of bracing members by taking stiffness and strength into account. A method was proposed for inelastic buckling design of monosymmetric I-beams, in which residual stresses and variations of bending moment along a beam were taken into account [26]. From literature review, it can be found that most of these previous studies on high strength steel flexural members focused on plastic resistances or local buckling and limited works studies the overall stability of high strength steel flexural members. Besides, no research studies are available on the global stability performance of high strength Q460GJ structural steel flexural members.

Lateral restraints offer an efficient way to preventing lateral torsional buckling and increasing the loading resistances of beams. In order to investigate the behaviour of GJ structural steel beams with lateral restraints, experimental tests were conducted on Q460GJ structural steel beams under a concentred load at the mid-span in this study. A total of eight doubly symmetric welded beams were tested. A special test set-up system was designed for the tests. Using the measured dimensions and material properties, finite element analysis (FEA) models incorporating initial geometric imperfections and residual stresses were established and verified by experimental results. Based on the validated FEA models, parametric studies were carried out and comparisons were made between numerical results and design buckling curves from Chinese steel structure design codes [27,28], American code [29] and Eurocode 3 [30]. In accordance with experimental and numerical results, design recommendations were proposed on global stability of Q460GJ structural steel beams.

2. Experimental program

2.1. Test specimens

A total of eight beam tests were carried out in this study. All the beams were fabricated of Q460GJ structural steel plates with

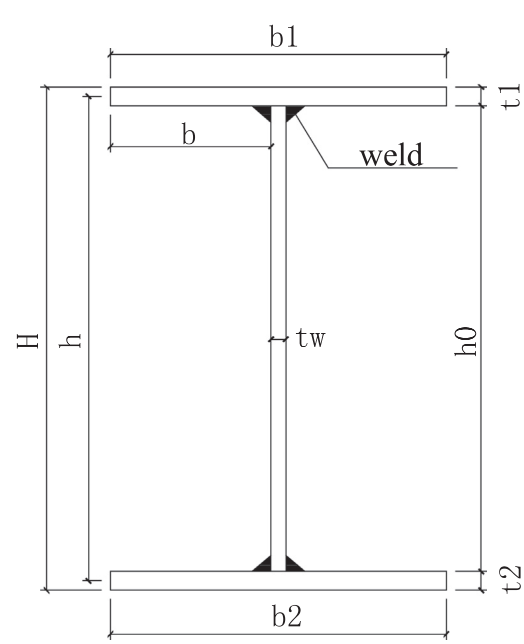

Fig. 1. Definition of symbols for cross section dimension.