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# Experimental and numerical studies on stainless steel tubular members under axial cyclic loading

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ABSTRACT

The fundamental behaviour of stainless steel tubular hollow section members under axial cyclic loading is presented in this paper. An experimental investigation on eight test specimens with varying global and local slenderness is conducted first, where the strength, fracture life, ductility, and energy dissipation capability are discussed in detail. A numerical study is then carried out to further elaborate the deformation/stress pattern, global and local buckling behaviour, and imperfection sensitivity of the members. The subsequent parametric study considers a broadened parameter matrix and thus enables a more comprehensive understanding of the global and local buckling behaviour of stainless steel tubular hollow section members. It is generally observed that the major stainless steel design codes provide conservative predictions for the compressive resistance of the members under cyclic loading, and a large dispersion of the FE-to-predicted ratio exists. A Continuous Strength Method (CSM) is shown to provide more consistent predictions. Due to the diverse failure modes observed in the parametric study models, large inconsistency also exists in the prediction of the post-buckling resistance of the FE models. A ductility-oriented design approach is proposed to enable a quick yet reliable prediction of the available compressive ductility of cyclically loaded stainless steel members.

## 1. Introduction

Stainless steel has been gaining increasing popularity in structural applications due to its favourable durability, ductility, weldability, aesthetic appearance, as well as improved fire resistance [1]. In addition, stainless steel is very suitable for cold processing due to its pronounced strain hardening. Although the initial higher cost compared to normal carbon steel has to some extent limited its widespread use in the past, people now start to realise that the low maintenance cost may make stainless steel more economical from a lifecycle design point of view [2]. Over the past two decades, extensive investigations have been conducted on stainless steel structural members, including columns, beams, and beam-columns, with particular focus on the understanding of their basic load carrying capacities under static loading conditions [3–21]. It has been revealed that due to the distinctive nonlinear stress-strain relationship with no evident yield plateau but substantial strain hardening, stainless steel members can behave differently from their carbon steel counterparts. In light of this, the applicability of the existing structural steel design principles to stainless steel has been carefully revisited, and modifications or new design approaches have been proposed where necessary.

The increasing understanding of the fundamental behaviour of stainless steel at material, section, and member levels leads to successful stipulation of stainless steel design codes [22–24]. Recent research interests have also been extended to concrete-filled members that utilise the benefit of composite constraining effect [25–27]. The fire performance of these members has also been studied [28,29]. Despite the significant research effort, there has been limited seismic evaluation of stainless steel members, and as a result the confidence of using these members for seismic-active regions is still lacking [30,31]. In particular, the potential for using stainless steel for bracing members is insufficiently explored. Braced frame is one of the most widely used lateral load resistance systems against earthquakes actions. During strong earthquakes, the diagonal bracing members are expected to have good ductility and contribute to energy dissipation through undergoing large inelastic cyclic deformations. In addition, certain post-buckling resistance needs to be maintained when the member is in compression. The axial load-displacement hysteretic behaviour of carbon steel tubular hollow bracing members has been the subject of investigation by many researchers [32–34]. A common finding was that the global and local (section) slenderness are two factors that greatly affect the hysteretic behaviour of the braces. The material performance under cyclic

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loading also essentially influences the fatigue life of the member. By a comprehensive survey of the available test data, Tremblay [35] developed empirical expressions for depicting some key bracing properties including buckling resistance, post-buckling resistance, tensile resistance, and fracture life of carbon steel braces. The experimental data pool was later enriched by Elchalakani et al. [36] and Goggins et al. [37] who proposed modifications to the existing design expressions. The potential benefit of concrete infill for steel tubular braces against local buckling was confirmed by Broderick et al. [38] and Sheehan and Chan [39]. In addition, finite element (FE) studies have been undertaken to further evaluate the hysteretic responses of braces with a broadened range of geometrical parameters [40,41]. For stainless steel bracing members, DiSarno et al. [42] found that the pronounced strain hardening of stainless steel can help delay local buckling in members subjected to axial compression. Nip et al. [43] conducted nine tests on stainless steel bracing members and found that these specimens have higher tensile and compressive resistance than carbon steel specimens.

In contrast to the extensive experimental and numerical investigations on carbon steel bracing members, there is still limited information available for stainless steel ones. In addition, reliable design methods that address the buckling strength and ductility properties of the stainless steel members under cyclic loading are insufficient. As stainless steel becomes more readily available and affordable for use in the construction industry, the seismic behaviour of bracing members of this material deserves further investigation. A particular reason, from the structural engineering point of view, to consider stainless steel for bracing members is its potential benefit of relatively high tensile ductility and pronounced strain hardening. In addition, the excellent corrosion resistance of stainless steel may make it a competitive solution for members hidden behind walls, where inspection and maintenance can be difficult. Another typical scenario where stainless steel members are designed to be under axial load is planar or spatial trusses. Some studies have already been conducted on this front [44], but the seismic response has not been considered.

This paper discusses the fundamental behaviour of stainless steel tubular hollow section members under axial cyclic loading. A total of eight specimens are tested, where the basic hysteretic responses, including tensile and compressive resistance, post-buckling resistance, ductility, and energy dissipation are evaluated. Global slenderness and local slenderness are considered as the two main parameters for the test programme. A numerical study is then carried out, shedding further light on the strength, stress pattern, global and local buckling behaviour, and imperfection sensitivity of the specimens. The parameter matrix is then broadened through a parametric study, based on which a set of design comments on the strength, post-buckling resistance, and ductility behaviour of stainless steel braces is finally made.

## 2. Experimental programme

### 2.1. Test specimens

A total of eight cold-formed stainless steel tubular specimens were tested. Each specimen consisted of a main tubular member, two grade Q235B (nominal $f_y = 235$ MPa) end-plates, and a series of grade Q235B stiffeners to strengthen the junctions between the main member and end-plates, as shown in Fig. 1. The tubular members were made from grade 304 austenite stainless steel plates to form rectangular or square hollow section (RHS or SHS) shapes and were finished by longitudinal welding. The main test parameters were cross-section shape, specimen length ($L$), and tube thickness ($t$). It should be noted that the specimen length $L$ is that between the top and bottom stiffeners. Four different section dimensions, namely, SHS 60 × 60 × 4, SHS 60 × 60 × 2, RHS 60 × 40 × 4, and RHS 60 × 40 × 2, were considered, and two specimen lengths, i.e., 2350 mm and 1450 mm, were employed. The measured dimensions of the sections are given in Table 1 with the symbols defined in Fig. 1. In particular, $b$ and $h$ are the overall width and depth of the section ($b \geq h$), $b_p$ and $h_p$ are the corresponding width and depth excluding the rounded corners, and $r_0$ is the outer radius of the arc corner.

The geometrical dimensions are related to global member slenderness ($\lambda_c$) and local section slenderness ($\lambda_s$) as defined by:

$$\lambda_c = \sqrt{\sigma_{0.2} A / N_{cr}} \tag{1}$$

$$\lambda_s = b_p / t\varepsilon \tag{2}$$

where $\sigma_{0.2}$ = measured material yield strength, i.e., 0.2% proof stress of the flat part of the stainless steel tube, $A$ = cross-section area, $N_{\mathrm{cr}}$ = elastic critical buckling load (based on the specimen length $L$ and a theoretical effective length factor $K$, i.e., $K = 0.5$ for ideal fixed-fixed end condition), $\varepsilon = (235E_0/210000\ \sigma_{0.2})^{0.5}$, in which $E_0$ is the measured Young's modulus of the material. The maximum $\lambda_c$ for the specimens is 1.29, which is smaller than the upper limit of 2.0 required in Eurocode 8 [45] for concentrically braced frames. In addition, the cross-section classification of the specimens based on the updated version of Eurocode 3, i.e., EN 1993-1-4:2006 + A1:2015 [23], is given in Table 1. For ease of reference, each specimen was designated with a specimen code using its nominal dimensions $b \times h \times t \times L$, e.g., specimen 60 × 40 × 4 × 2350.

The material properties of the specimens were determined by tensile coupon tests. For each section type, the coupons were taken from the flat part of the three non-welded sides of the tube in the longitudinal direction. The coupon specimens were prepared in accordance with ISO 6892–1 [46], and were tested by a MTS testing machine under displacement control. Two strain gauges and a calibrated extensometer of 50 mm gauge length were used to monitor the strain development conditions. The average material properties, including the 0.2% proof stress ($\sigma_{0.2}$), tensile strength ($\sigma_{\mathrm{u}}$), Young's modulus ($E_0$), elongation after fracture ($\varepsilon_{\mathrm{f}}$), and the basic Ramberg-Osgood parameter ($\eta$) are summarized in Table 2. As expected, the material generally exhibits high tensile ductility.

### 2.2. Test setup, instrumentations, and test procedures

The specimens were subjected to cyclic axial loading via the test setup shown in Fig. 2(a). The bottom end of each specimen was fully fixed to the strong floor while the top loaded end was restrained rotationally and laterally, with only the axial displacement allowed. Such a fixed-fixed boundary condition corresponds to a theoretical effective length factor of $K = 0.5$. By confirming that minimal end rotation was observed during the tests, the effective length for calculating the global slenderness was taken as 0.5$L$ [43]. The cyclic load was applied by a servo-controlled hydraulic actuator with a maximum capacity of 3000 kN.

The applied axial load was measured by the load cell of the actuator, and the deformation and displacement responses of the specimens were monitored via a series of strain gauges and linear variable differential transformers (LVDTs), as illustrated in Fig. 2(b). The strain gauges were applied to the member mid-span and end cross-sections, which are critical locations where local buckling and final fracture are most likely to occur. Another purpose of the strain gauges which were placed around the perimeter of the section was to ensure that the axial load was applied concentrically. The LVDTs enabled a detailed measurement of the member displacement conditions, including axial displacement at the loaded end, mid-span deflection, movement of end restraints, and possible torsional displacement of the member.

The normalised cyclic axial displacement $\Delta/\Delta_y$ was considered as the controlling parameter for the loading protocols, where $\Delta$ is the axial displacement recorded at the loaded end, and $\Delta_y$ is the yield displacement estimated based on the member length $L$ and the "yield strain" at the 0.2% proof stress. The loading history has been found as a critical factor affecting the ductility of members under axial loading [36]. Two loading protocols were considered in this study. For specimen