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Fundamental behaviour of high strength and ultra-high strength steel subjected to low cycle structural damage

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ABSTRACT

Along with the rising application of high strength steel in civil engineering practice, it has become imperative to gain comprehensive understanding of the elastic and plastic behaviour of these materials under given strain or stress histories. For seismic analysis of structures in earthquake prone areas, this paper aims to analytically and theoretically study the cyclic behaviour of high strength steel tubes, with individual applications or incorporated in fabricated structural elements. Several low cycle tension-compression tests are conducted on high strength (grade 800) and ultra-high strength (grade 1200) steel coupons extracted from tubes. Parameters such as number of cycles, strain/stress amplitude and increment size are studied in the behaviour of cyclically strained material and its preserved mechanical properties. Numerical analysis is also conducted incorporating combined nonlinear hardening models. As opposed to conventional structural mild steel both grades of steels considered in this study exhibit cyclic softening with plastic straining having a more prominent strength reduction in higher strengths of steel. Cyclical damage applied on high tensile steel evidently influences the preserved mechanical properties of microstructure at fracture. Combined nonlinear plastic hardening and relevant parameters proposed in this study for two grades of high strength steel materials are calibrated and verified against hysteretic experimental results and proposed for further analytical and numerical modelling.

1. Introduction

The application of high strength steel materials has recently increased in various civil constructions and is found to have convenient structural properties and cost efficiency compared to conventional mild steel material. Following this increasing trend there is a necessity to gain an extensive understanding of the mechanical properties of these materials under relevant loading conditions. Previous studies are found mostly investigating the behaviour of high strength steel structural elements with material steel grades of up to around 700 MPa [1–6]. However, in more recent studies higher grades of steel (with nominal yield strength of 800 MPa–1200 MPa) have also been taken into consideration to investigate the behaviour of ultra-high strength steel beams, columns, girders and other types of structural elements [7–11]. An application for high strength steel material proposed and widely investigated in literature, is utilizing these materials in “dual-steel” moment resisting frames in which high strength steel acts as non-dissipative members while mild steel is used in dissipative zones [12–15]. In these systems, high strength steel is used in order to increase the seismic performance of structural system by limiting plastic behaviour in columns and guaranteeing the weak-beam/strong-column behaviour [12,14]. As a current development, hybrid fabricated sections are proposed in which a combination of high strength steel tubes and mild steel plates are incorporated, taking advantage of these modern materials in load bearing structural elements [16–19]. In these sections, taking benefit of the interaction between different grades of constituting steel elements, both strength and ductility of the structural element are enhanced.

Following the numerous amount of work on conventional mild steel under extreme loadings such as cyclic, impact and fire conditions [20–24] high strength and ultra-high strength steel in form of tubular elements have recently been investigated under potential extreme conditions [25–29] due to their light weight and convenient geometry. Understanding the hysteretic response of high strength steel material is of significant importance for seismic analysis of members especially in case of energy dissipating members constituting of these high tensile materials. The mechanical properties and plastic behaviour of high strength material is of importance both during seismic loading and beyond that which

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is where the structure continues to undergo post-earthquake service loads. The aim of material scale examinations on high strength steel specifically under cyclic loadings include material characterisation and modelling, obtaining preliminary constitutive equations and failure or fracture mode prediction. High tensile structural steel with yield strengths within the range of 300–500 MPa have previously been experimentally tested to obtain the hysteretic response and relevant parameters such as hardening and ductility [30–33] and steel grades up to 600 MPa under low cycle damage have been constidered. Nip et al. [32] tested carbon and stainless steel under low cycle fatigue and obtained a combined hardening model to be incorporated in numerical models. Two different test arrangements of axial and bending were considered and cyclic parameters of either type was compared [32]. In other research work constitutive material models were established based on various experimental loading patterns which were implemented in nonlinear time history analysis of steel frames [30] and quasi-static simulation of steel beam-columns [33]. Effect of cyclic loading on the occurrence of brittle failure and ductility was studied by Iwashita et al. [31] and a method was proposed to evaluate the brittle failure under various loading conditions. In steel grades higher than 500 MPa, Silvestre et al. [34] tested a range of (ferritic) steel material including high and ultra-high strength steel with approximate yield stress within the range of 200–1200 MPa and developed a mixed hardening model. However the test coupons were extracted from 1.5 mm sheets and limited to constant strain amplitudes of 2%. In terms of standard recommendations for design purposes, previous studies [18,35] have focused on the ductility of HSS and UHSS steel materials and comparison have been made with regards to recommended standard criteria against a variety of design standards showing that these steel grades fail to meet some of the proposed requirements which consequently affects the design and prediction of section performance against local buckling. This highlights the demand for further investigations focused on high tensile steel grades to derive practical design recommendations which are not included in current available standard classifications. Experimental and numerical model proposed in this study provide primary knowledge for these investigations.

The present study, examines the hysteretic response of high strength (grade 800) and ultra-high strength (grade 1200) steel material to contribute to the limited data currently available on these grades of steels in structural applications. All test specimens are extracted from high and ultra-high strength circular steel tubes and tested under strain and stress controlled amplitudes. Strain controlled tests are conducted in two types of constant and incremental amplitudes. Number of cycles and strain amplitude percentage are the two parameters considered in the constant strain controlled tests. Incremental strain amplitude tests are also conducted with varying strain steps. The obtained results show the occurrence of cyclic softening in both high and ultra-high strength steel materials. Hysteretic curves for both high strength steel materials are analysed in terms of strength softening, preserved strength and ductility and its correlation to final fracture, energy absorption etc. From hysteretic responses, a simplified stress-strain formulation based on the Ramberg-Osgood model is suggested. Besides, relevant kinematic/isotropic plasticity parameters are proposed for high strength and ultra-high strength steel tubes which are applicable for modelling various scales of structures and structural components.

2. Cyclic testing of high strength steel (HSS) and ultra-high strength steel (UHSS) specimens

2.1. Test setup

A series of experimental tests were designed and conducted to obtain the necessary parameters for modelling the cyclic behaviour of HSS and UHSS steels. Various test paths were considered with different combinations of tension and compression straining. All monotonic and cyclic test specimens were extracted directly from grade 800 (HSS) and grade 1200 (UHSS) circular steel tubes, having a 90-degree angle from the tube weld. Manufacturing process and detailed mechanical properties of these steel tubes are the same as tube material reported in authors' previous research work [36]. Due to the thin-walled geometry of tube (nominal thickness of 3.2 mm and external diameter of 76.1 mm) and also limitations in the minimum gauge length for strain measurement, the dimensions of test specimens were chosen in a way to reduce the chance of buckling during the compression phase of cyclic test. These dimensions follow the ASTM E606-04 standard practice guidelines [37] for strain controlled fatigue testing and are presented in Fig. 1. Similar to previous literature on thin-walled specimens [38], strain corresponding to buckling initiation was found by conducting trial tests, to assure buckling does not occur within the strain levels considered in the present study.

In all cyclic specimens the length of reduced section to nominal thickness is around 3.8 and the measured gauge length to nominal thickness ratio is approximately equal to 3. However, to assure that buckling is fully prevented, an anti-buckling fixture was also designed and utilised during each test. Based on previous literature, in-plane compression testing can be done using either side loading, or using constraint, to suppress buckling in the thickness direction [39]. The anti-buckling fixture used in this study consists of two steel segments covering each side of the specimen, fastened with high strength bolts. A layer of high performance grease was applied between the specimen surface and fixture to prevent friction. The anti-buckling fixture is specifically designed for testing the tube specimens with grooves designed to run along the specimen reducing the contact in curved areas. Fig. 1 shows the shape and cross-section of the fixture covering the cyclic specimen.

Test specimens were loaded in the Instron 8802 servo-hydraulic testing machine and the data acquisition was done through the machine readings in addition to precise strain measurement of gauge length obtained from a non-contact MTS LX500 laser extensometer with a strain resolution of 0.001 mm and scan rate of 100 scans/s. Standard tensile tests were also conducted on both HSS and UHSS tube materials to gain understanding of the typical mechanical properties of these materials under quasi-static monotonic loading. The cyclic test setup is shown in Fig. 2. Quasi-static displacement rate of 0.3 mm/min was applied to all specimens under monotonic and cyclic loadings.

2.2. Test paths and outcomes

Various types of monotonic, strain controlled and stress controlled cyclic tests were conducted on both HSS and UHSS steel materials. The variables considered in the tests were amplitude, strain step, number of cycles and residual strain applied to the specimen before cyclic loading. Two values of maximum plastic strain were chosen for each material one of which is close to the strain corresponding to ultimate tensile strength (ϵ_{UTS}) and the second a lower percentage of that strain. Tests were conducted applying different number of cycles (N) for each of the materials. Strain was applied to specimens either with constant amplitude (A_ϵ) or increasing steps of strain amplitudes (Δ_ϵ) and in some cases a residual strain (R_ϵ) was applied by an initial displacement controlled monotonic loading followed by the strain cycles. In addition to the above mentioned cases, stress-controlled cyclic tests with constant stress amplitudes (A_σ) were conducted at two different stress values. All strain/stress paths applied to HSS and UHSS are shown in Table 1. Test types (a) and (b) vary in terms of the amplitude of applied strain while in test type (c), number of cycles (N) is the factor which was increased from 8 to 12. Keeping both