ΚΥΚΛΙΚΕΣ ΔΟΚΙΜΕΣ ΚΑΙ ΣΥΜΠΕΡΙΦΟΡΑ ΣΕ ΘΡΑΥΣΗ ΣΕΙΣΜΙΚΩΝ ΑΠΟΣΒΕΣΤΗΡΩΝ ΑΠΟ ΧΑΛΥΒΑ ΥΨΗΛΗΣ ΑΝΤΟΧΗΣ ΚΑΙ ΑΝΟΞΕΙΔΩΤΟ ΧΑΛΥΒΑ

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ΠΕΡΙΛΗΨΗ

Ένας αποτελεσματικός τρόπος απόσβεσης της σεισμικής ενέργειας σε κατασκευές είναι μέσω μεταλλικών στοιχείων με μεγάλη ικανότητα ανελαστικής παραμόρφωσης. Κυλινδρικά χαλύβδινα στοιχεία με σχήμα κλεψύδρας στα καμπτικά μέρη έχουν πρόσφατα χρησιμοποιηθεί ως σύστημα απορρόφησης ενέργειας σε προεντεταμένες συνδέσεις δοκού-υποστυλώματος με δυνατότητα αυτό-επαναφοράς. Η παρούσα εργασία αξιολογεί την υστερητική συμπεριφορά αυτών των στοιχείων κατασκευασμένα από χάλυβα υψηλής αντοχής και ανοξείδωτο χάλυβα. Η δυνατότητα απορρόφησης ενέργειας και η πλαστιμότητά τους αξιολογήθηκαν μέσω είκοσι έξι δοκιμών χρησιμοποιώντας διαφορετικά πρωτόκολλα κυκλικής φόρτισης και διαφορετικές γεωμετρίες. Οι δοκιμές έδειξαν ότι τα εν λόγω στοιχεία κατασκευασμένα από υψηλής αντοχής και ανοξείδωτο χάλυβα έχουν σταθερή υστερητική συμπεριφορά, εξαιρετική πλαστιμότητα και υψηλή ικανότητα θραύσης. Οι συσκευές από ανοξείδωτο χάλυβα έχουν γενικά καλύτερη συμπεριφορά από εκείνες που κατασκευάζονται από χάλυβα υψηλής αντοχής.

CYCLIC TESTS AND FRACTURE BEHAVIOUR OF SEISMIC STEEL DAMPERS MADE OF HIGH PERFORMANCE STEEL

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1. ABSTRACT

Steel yielding hysteretic devices provide a reliable way to increase the energy dissipation capacity of structures under seismic loading. Steel cylindrical pins with hourglass shape bending parts (called web hourglass shape pins - WHPs) have been recently used as the energy dissipation system of post-tensioned connections for self-centering steel moment-resisting frames. This work evaluates the cyclic behaviour of WHPs made of high-strength steel and two grades of stainless steel, i.e. austenitic grade 304 and duplex. Design rules for WHPs are established using principles of mechanics. Twenty-six tests using different cyclic loading protocols and different WHP geometries were conducted. The tests showed that the WHPs have stable hysteretic behaviour and high fracture capacity. WHPs made of duplex stainless steel have the most favorable and predictable performance for seismic applications.

2. INTRODUCTION

An efficient seismic design strategy is to concentrate damage in steel yielding devices and protect the main structural members (e.g. beams, columns and braces) from yielding with capacity design rules. Steel yielding devices increase the energy dissipation capacity of the structure, exhibit stable and predictable hysteretic behavior, have long-term reliability and insensitivity to ambient temperature, and when designed to be accessible and easily replaceable can significantly reduce damage repair costs and downtime in the aftermath of a strong seismic event ([1], [2], and [3]). Steel cylindrical pins with hourglass-shape bending parts (called web hourglass pins – WHPs) have been recently used by the authors ([4], [5], and [6]) as the energy dissipation system of a steel post-tensioned (PT) beam-column connection for self-centering moment-resisting frames (SC-MRFs).

Pilot tests on WHPs showed their superior energy dissipation and fracture capacity [1]. However, more work is needed to assess the hysteretic behavior and low-cycle fatigue performance of WHPs for high performance steel materials such as high strength steel (HSS) and stainless steel (SS). The use of HSS and SS in structural engineering is now included in international standards [7]. HSS has nominal yield strength between 460 and 690 MPa, excellent weldability and high ductility. SS is extremely durable, has good corrosion resistance, improved fire resistance and easy maintenance. There is limited experience on the low-cycle fatigue and fracture capacity of SS for seismic applications. SS grades are divided into three categories: austenitic, ferritic, and duplex. Austenitic is the most common type of SS. Duplex SS (referred to herein as SSD) is at least twice stronger than the common austenitic grades and highly resistant to corrosion cracking.

This paper presents an experimental investigation of the hysteretic behavior and fracture capacities of WHPs. The experimental program consists of twenty – six monotonic and cyclic tests using different loading protocols and two different geometries of WHPs made of HSS and SS. The steel grades considered are: HSS carbon steel grade M1020; austenitic SS grade 304; and SSD. Analytical expressions to predict the strength and stiffness of WHPs and to design their supporting plates are also presented.

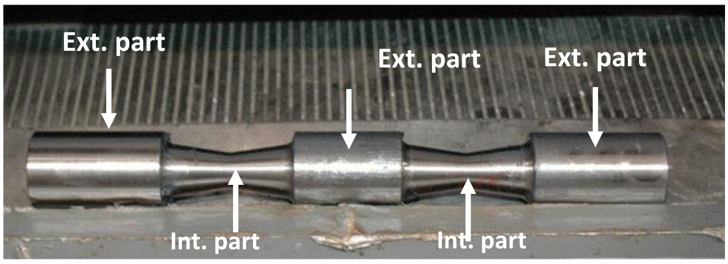
3. EXPERIMENTAL PROGRAM

3.1 Test specimens

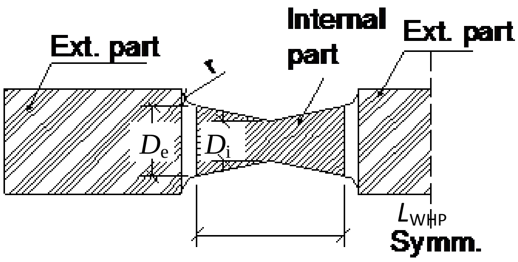
The WHP geometries are based on a prototype six-story steel building designed as a SC-MRF in Vasdravellis et al. [4]. The geometrical parameters of a WHP are defined in *Fig. 1*. Two WHP geometries were tested. The first geometry (small WHPs) has D_e= 20 mm, D_i= 14 mm and L_{WHP}= 40 mm, and the second one (large WHPs) has D_e= 28 mm, D_i= 18 mm and L_{WHP}= 65 mm. The small WHPs are made of three different materials, i.e. HSS grade M1020, SS grade 304 (denoted as SS304) and SSD grade 2205. The large WHPs were made of HSS grade M1020 and SS304. To keep the dimensions reasonably compact, cold-drawn conditions were used for the production of the WHPs made of SS304, which resulted in considerably higher strength of the SS304 material. Specimens are denoted as CS-WHP1, SS-WHP1, SSD-WHP1, CS-WHP2 and SS-WHP2 with CS referring to carbon HSS, 1 to the small geometry and 2 to the large geometry.

3.2 Testing apparatus and instrumentation

The WHPs were tested in a configuration mimicking the actual layout in a PT connection as shown in *Fig. 2*. A WHP was inserted into aligned holes drilled on external thick plates representing the supporting plates welded to the column flange and on internal plate representing the web of the beam. The external and internal plates were welded on a strong fixed plate. The WHP was fitted into the plates with minimum clearance. To measure the WHP displacement, two linear variable differential transformers (LVDTs) were used. One LVDT was attached to the supporting plates and another one to the web.



a)



b)

Fig. 1. a) Photo of a WHP; b) Geometric parameters and assumed static system for half a WHP.

3.3 Material property tests

Material property tests consisted of uniaxial tensile tests on coupons produced from the same batch used to produce the WHPs. Three coupons were tested for each material. The stress-strain curves showed that M1020 has significantly lower ductility than SS304 and SSD. The SS coupons have a more rounded stress-strain curve without a well-defined yield point and exhibit significant hardening behavior. Cold-drawn production of the SS304 resulted in a significantly higher yield stress (520 MPa) than the annealed condition of the same material which has nominal yield strength equal to 300 MPa. SSD material has a mean yield stress equal to 543 MPa.

3.4 Loading protocols and testing procedure

Specimens CS-WHP1, SS-WHP1 and SSD-WHP1 were tested using different loading protocols. The first test was a monotonic test. The second test used the cyclic loading protocol prescribed in ANSI/AISC 341-10 [8]. The third loading history follows the recommendations of FEMA-461 [9]. To assess the low-cycle fatigue behavior, a constant-amplitude (CA) loading history was used. The applied displacements were equal to 6 mm ($5\delta_y$), 6 mm ($7\delta_y$) and 9 mm ($9\delta_y$) for specimens CS-WHP1, SS-WHP1 and SSD-WHP1, respectively, where δ_y is the WHP yield displacement. Specimen CS-WHP1 was further subjected to three more CA protocols with amplitudes 4 mm, 5 mm, and 8 mm, and one cyclic protocol with randomly varied imposed displacements.

To assess the WHP performance under non-standard loading protocols, a near-fault loading history and a loading history simulating collapse conditions of the SC-MRF were used. The near-fault loading protocol is adopted from Krawinkler et al. [10]. The collapse loading protocol consists of ten initial cycles at δ= 1.25 mm, four cycles at the range δ= 2.5 - 5.5 mm with the rest cycles ranging from 7.5 to 10.5 mm imposed displacement.

CS-WHP2 and SS-WHP2 were tested using one monotonic loading and one cyclic loading according to FEMA-461.

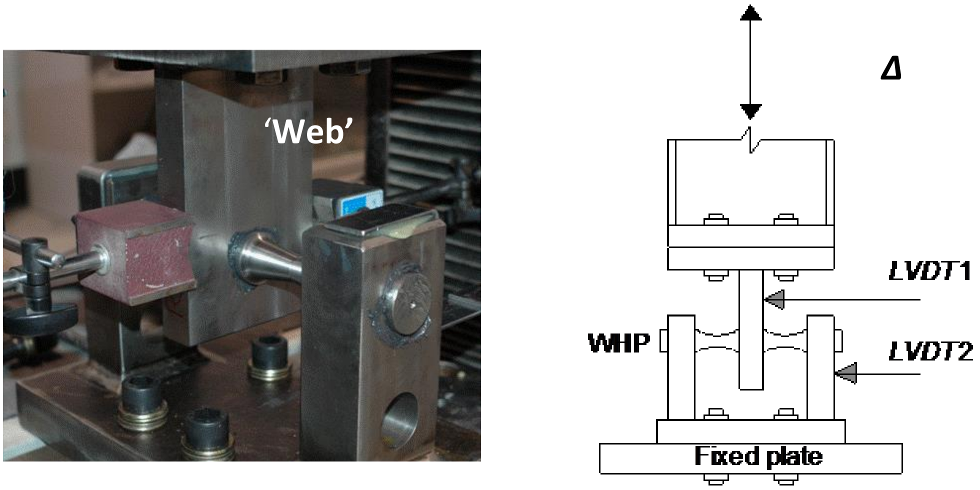


Fig. 2. Test setup and instrumentation

4. RESULTS AND DISCUSSION

4.1 Cyclic hysteretic behavior

Fig. 3 shows the hysteresis of CS-WHP1, SS-WHP1 and SSD-WHP1 under the AISC and the FEMA-461 loading protocols and *Fig. 4* shows the hysteresis of CS-WHP2 and SS-WHP2 under the FEMA-461 protocol. The monotonic force-displacement curves are superimposed and denoted as "Mono". All specimens show stable hysteresis and high fracture capacity. WHPs do not fracture for cyclic displacements far beyond those expected under the MCE. A characteristic of the WHP hysteresis is the slight pinching effect, i.e. the flat region at zero force. This behavior is attributed to the combined slip and ovalization of the holes that takes place at the interface. WHPs made of SS sustained more cycles than WHPs made of M1020. WHPs made of SS304 and SSD show similar performance under the AISC and FEMA-461 protocols.

Fig. 5 illustrates typical fracture modes of the WHPs under cyclic loading. Fracture commonly initiated from Section 1 at the end of the bending part close to the web. In most of the tests cracks were subsequently formed in Sections 2 and 3 showing that plastic deformations are spread along the length of the WHP bending parts. In WHPs made of SS304 visible cracks were formed only in Sections 1 and 3. Ultimately, all WHPs failed due to fracture at Section 1. Therefore, failure of WHPs is controlled by flexural deformations, which is more desirable than plastic shear failure. WHPs showed excellent ductility with values greater than ten. SS-WHPs have higher ductility than CS-WHPs, while WHPs made of SS304 have the largest ductility. More details are provided in Vasdravellis et al. [11].

Figs. 3 and 4 show that the monotonic force-displacement curve of the WHPs follows the cyclic envelope except for WHPs made of SS304. During the initial cycles, SS-WHP1's cyclic envelope is in agreement with the monotonic curve; however, the hysteresis shows

significant hardening after few cycles. The cyclic increase in strength is about 15% for the AISC, FEMA-461 and CA protocols. Similar behavior is observed for SS-WHP2. This behavior is not observed for WHPs made of SSD. Since the hysteresis of the WHPs made of SS304 is not reliably predictable, at least in the present experimental study, it is concluded that SSD consists a more suitable material for seismic energy dissipation.
WHPs passed successfully the near-fault loading protocol without strength degradation or fracture. No fracture was observed in the collapse tests.

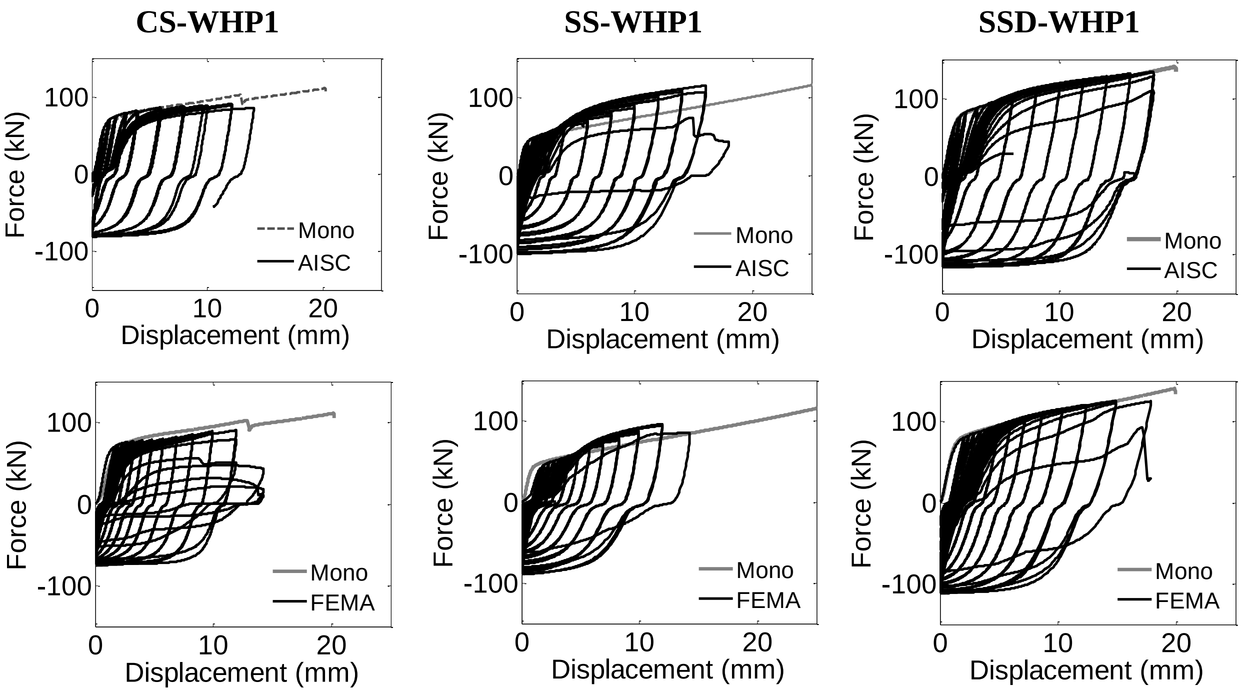
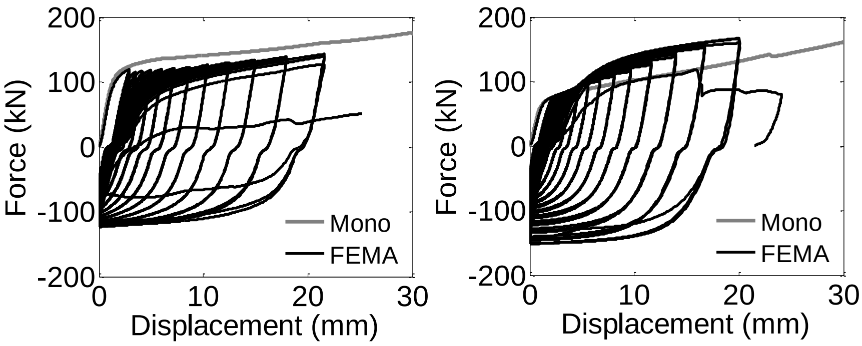


Fig. 3. Hystereses of the small WHPs under the AISC and FEMA-461 cyclic protocols



a) CS-WHP2 *b) SS-WHP2*

Fig. 4. Hysteresis of the large WHPs under the FEMA-461 loading protocol

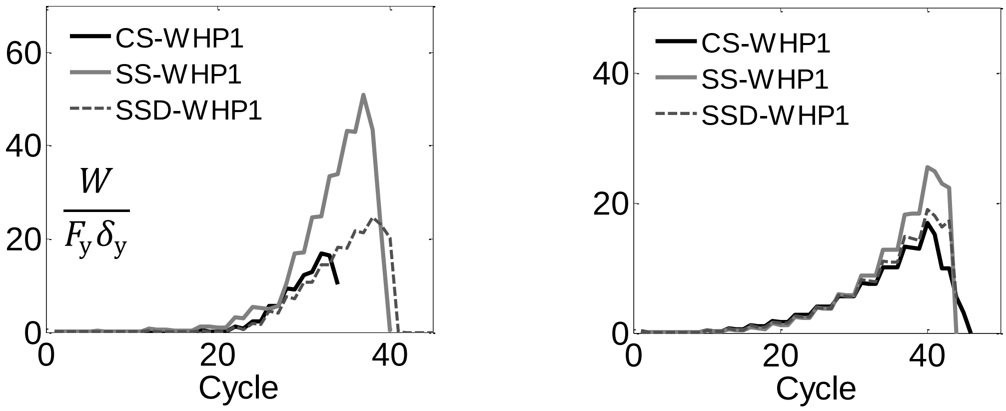
4.2 Energy dissipation capacity

The energy dissipation (ED) capacity of WHPs is evaluated in this section. The energy dissipated in each cycle was calculated as the area enclosed in the force-displacement curves. To provide a consistent comparison, the dissipated energy W in each cycle was divided by the product $\delta_y F_y$, where Fy is the force corresponding to δ_y. *Fig. 6* plots W/(

$\delta_y F_y$) of the small WHPs under the AISC and FEMA-461 loading protocols. SS-WHP1 shows similar ED capacity with CS-WHP1 and SSD-WHP1 during the initial cycles but its ED capacity is significantly increased at the later cycles due to hardening. SSD-WHP1 shows larger ED capacity than CS-WHP1. Similar conclusions are drawn for the ED behavior of the large WHPs (not shown here). For more details the reader is referred to Vasdravellis et al. [11].

a) *b)*

Fig. 5. a) Large displacement of the SS-WHP2 specimen under monotonic loading; b) fracture (typical) of a WHP under cyclic loading



a) b)

Fig. 6. Comparison of the energy dissipation of the small WHPs under: a) the AISC loading protocol; and b) the FEMA-461 loading protocol

5. CONCLUSIONS

This paper presented an experimental program that evaluates the hysteresis of steel cylindrical pins with hourglass shape bending parts (called web hourglass shape pins - WHPs) made of high strength steel (HSS), austenitic stainless steel (SS) and duplex stainless steel (SSD). Based on the findings of this study, the following conclusions are outlined:

1. Monotonic tests showed that WHPs are very ductile and do not fracture under monotonic loading. This feature can be very advantageous under loading that imposes excessive monotonic displacements such as progressive collapse conditions due to a loss of column scenario.

2. Under cyclic loading WHPs show stable hysteresis, high energy dissipation and high fracture capacity. Fracture occurs at displacements far beyond those expected under the maximum considered earthquake.
3. WHPs made of SS outperform those made of HSS under cyclic loading as they have larger energy dissipation and fracture capacities.
4. WHPs made of SS show significant cyclic hardening. No degradation of strength and stiffness was observed in most of the same-amplitude repeated inelastic cycles.
5. SSD is more reliable than SS as it has a more predictable behavior, and so, it is a favorable material for seismic applications.
6. WHPs easily pass near-fault and collapse cyclic loading protocols without fracturing. In addition, the cyclic envelope of the collapse cyclic loading is identical to the monotonic behavior for all WHPs.

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