High strength tubular columns and connections under earthquake, fire loading and fatigue

G. Zanon, A. Kumar, O. S. Bursi, F. Ferrario, A. Giacobbe

High strength steel (HSS) has been available for many years. However, its use in onshore engineering is quite restrictive. Nonetheless very recently, there was a growing trend for the use of HSS in tubular structures thanks to Eurocode 3 Part 1-12 (2006) that extended its scope to steel grades up to S690/S700MC. Nonetheless, Eurocode 3 Part 1-12 imposes many limitations at thematerial, structural and design level. The ambitious targets of two EU funded –ATTEL and HITUBES – projects are to increase the performance of tubular structures, reduce weights, construction and operating costs by change in conceptual design and implementation of HSS. In a greater detail, the intent of the ATTEL project, is to promote the use of HSS members endowed with circular hollow sections in buildings subject to earthquake and fire, in order to understand the actual behaviour of HSS material and to show the possible benefits with respect to mild steel. The buildings were realized with TS590 for steel columns and S275 for beams in order to satisfy the capacity design criterion for columns and beams under earthquake loading. The preliminary design of these structures leaned towards two fundamental conclusions: i) the cost benefits related to the use of HSS columns in braced frames, which are mainly subjected to axial loads and low bending moments; ii) the cost benefits related to the use of HHS columns in unbraced frames only achieved along the main direction and for "medium" earthquake loading (<0.25g). Physical tests both on full scale beam-to-column joints and column base joints to be performed at the University of Trento will allow details for these important components to be checked. As far as the HITUBES project is concerned, the main work regards members and joints subject to monotonic, low-cycle and high-cycle fatigue loading. In particular, the project is focusing on: i) extraction of tubular welded and bolted joints from two case studies, i.e. a footbridge and a railway bridge, respectively; ii) definition of weld condition –overmatching and undermatching – electrode selection and post-weld treatment –peening- for welded tubular joints.

Keywords: High strength steel, circular hollow section, building, bridges, earthquake, fire, fatigue, undermatching, overmatching

INTRODUCTION

In recent years application of high strength steel (HSS) is increasing in engineering solutions. HSS has been successfully implemented in auto and ship industries [1, 2, 3]. The application of HSS brings weight saving, cost saving, fuel economy, safety and environmental benefits [1, 2]. The application of higher grades of HSS in civil engineering structures subjected to natural actions for instance seismic, hurricane, fire and anthropic is still limited. Some references [4, 5, 6] advocate the implementation and advantages of HSS in civil engineering structures like bridges and buildings.

Though Eurocode 3 Part 1-12 [7, 8] extends its scope to steel grades up to S690/S700MC, many limitations exist at the material, structural and design level. There is little said about HSS welded connections under fatigue loading. The undermatched electrodes approach suggested in Eurocode 3 Part 1-12 in order to render the welds more ductile and less prone to cracks; improved welding techniques should be conceived, in order to improve quality and fatigue resistance of welded joints [9, 10, 11] also in the presence of a corrosive environment [12, 13]. Use of HSS can present tremendous opportunities for weight savings, but to achieve true economy the weight savings must be complemented with proper attention to design and fabrication details [14]. Circular hollow sections (CHS) provide aesthetic architecture and better aerodynamic performance. Eurocode EC3-1-1 is too conservative for circular sections of S460 and higher steel grades [15].

Designers are continually faced with the challenges imposed by extreme forces, in activities such as the design of buildings, foot- and cycle-bridges to withstand high winds or, for instance to minimize earthquake damage. Natural disasters occurring in the last few years, like those due to Katrina, Ivan and Rita hurricanes and the earthquake of Bam, Iran in 2003, stressed the need to achieve more accurate and safer design against extreme natural forces [16, 17]. The pedestrian induced vibration of the Millennium Bridge [18] showed that extreme pedestrian loading may cause major serviceability problems.

The two RFCS projects ATTEL [19] and HITUBES [20] aim

Gabriele Zanon, Anil Kumar, Oreste S. Bursi, Fabio Ferrario
Università di Trento, Italy

Alessandro Giacobbe
Tenaris Dalmine, Dalmine, Italy

at implicating the tubular sections made of HSS in civil engineering structures. In detail, ATTEL project aims at developing the design procedures to make use of concrete filled HSS tubular columns in building structures under fire and seismic loadings. The HITUBES project intends to promote the use of HSS members and joints with circular hollow sections in flexible structures like footbridge and railway bridge, subjected to wind, anthropic and fatigue loading, in order to understand the actual behavior of HSS material and to show the possible benefits with respect to mild steel.
The main activities and results are presented in Section 2 for the ATTEL and section 3 for the HITUBES project, respectively. Section 4 describes the problems handled in welding of high strength steel tubes in the course of the two projects. Section 5 concludes the paper.

ATTEL PROJECT

In recent years the community has understood the importance of facing correctly the exceptional events such as earthquake and fire, in order to reduce the risks deriving from these phenomena. For a correct approach in design of structures, it is very important to consider beside the static actions also the exceptional ones. Both the Italian National Code [21] and the Eurocodes [22, 23, 24] consider now also the exceptional action - seismic and fire action - as fundamental actions to design the structures.
HSS that until now was mainly used in mechanical applications can offer relevant benefits respect to the use of mild steel. HSS can be exploited to design structures which guarantee safety both under static and exceptional actions. The aim of our work is to underline the advantages deriving from the use of circular hollow sections, which offers excellent structural and architectural properties, in the realization of HSS columns for important buildings.
Designers are aware of the impossibility to have a unique solution. Each solution must represent the best compromise between all parameters or aspects that the designer has to take in consideration when designing a structure. It is known that the use of circular sections has major mechanical and architectural advantages. On the other hand the benefits of using of HSS respect to mild steel in order to realize circular columns has been scarcely studied. HSS behaviour is considerably different from mild steel because it exhibits a considerably lower material ductility. For this reason HSS can be used for elements for which a ductile behaviour is not required. Table 1 shows typical values of mechanical properties of HSS.
The ratio Benefit/Cost is still low. In detail, there is an increase of costs due to the better qualities of the material; benefits are bigger because of the use of less material to produce the elements and use of less manufacturing products in order to obtain all the parameters to satisfy the safety requisites.
In order to choose between HSS and mild steel, the designer has to properly consider the actions to be applied on the structure.
In order to study actual buildings, the ATTEL project considers only three different types of buildings commonly used both for shopping centres and for offices. Besides static loading the studied buildings are subjected to three exceptional actions. In particular:
- building subjected to fire load;
- a building subjected both to seismic (medium earthquake with ag<0.25g) and fire load;
- a building subjected both to seismic (fort earthquake with ag>0.25g) and fire load.

For each structures the economic comparison between the use of HSS (S590 manufactured by Tenaris Dalmine) and mild steel (S355) is proposed.
The preliminary analysis provided important results for the different types of buildings which were considered and the results are thereafter summarized.
The use of HSS for the production of columns is suitable in the case of pure steel braced frames, where the main action on the columns is the axial load and where the bending moment is small [19].
In the case of stocky columns, the economic benefits owing to the use of HSS are greater than those with greater slenderness columns. If one compares the cost between structures with HSS column (S590) and structures with mild steel (S355), the economic benefit can be achieved about 30 percent [26].
In the case of structures subjected to both static load and exceptional actions, the best solution exploits the use of different frames along the two main directions. The structure obtained from the combined use of a moment resisting frame along one main direction and a braced frame or frame with concrete cores or concrete wall along the other main direction, is a favourable solution, because the columns are subjected to bending moment only along one main direction. The use of circular hollow sections with HSS in order to realize concrete fillet tubular columns allows to design the columns (diameter and thickness) under the static load and to obtain, in the case of medium earthquake (ag <0.25g), the satisfaction of the capacity design in agreement with Eurocode 8 [24]. If the columns are designed with mild steel, the geometry for static load has to be increased, in order to satisfy the capacity design requirements.
The results of the above-mentioned structures subjected to fire load are reported in Table 2 and 3, respectively, points out the advantages of the use of HSS for circular columns for bare steel

TAB. 1
Typical Values of Mechanical Properties of HSS [25].
Valori tipici delle proprietà meccaniche degli acciai ad alto snervamento [25].

		Minimum Yield Strength (MPa)				Tensile Strength (MPa)			Minimum Elongation long %
Grade ↓	WT (mm) →	≤12	>12 ≤20	>20 ≤40	>40 ≤50	≤20	>20 ≤40	>40 ≤50	All
TS460		460	460	440	430	550/720			17
TS590		590	590	550	500	700-870	650-820	590-760	16
TS690		690	690	650	615	770/960	720/900	670/850	16
TS770		770	750	700	670	820/1000	750/930	720/900	15
TS890		890	870	850	820	940/1110	920/1090	870/1040	14

TAB. 2
Fire resistance for CHS columns.
Resistenza al fuoco per colonne a sezione circolare cava (CHS).

Prototype structure with CHS (Circular Hollow Sections) columns				
Steel Grade	Prescriptive approach R [min]		Performance-based approach R [min]	
Fire - Case 1	28	34	38	43
Fire - Case 2	55	65	55	65
Fire - Case 3	53	63	53	59

TAB. 3
Time of Resistance for CHS Columns.
Tempo di resistenza per colonne a sezione circolare cava (CHS).

Prototype structure with CFT (Concrete Fillet Tubular) columns				
Steel Grade	Prescriptive approach R [min]		Performance-based approach R [min]	
Fire - Case 1	79	79	91	91
Fire - Case 2	100	100	100	100
Fire - Case 3	91	91	92	90

columns. HSS can increase the fire resistance more than that required respect to mild steel. In the case of concrete fillet tubular, the increase of fire resistance owing to the use of the HSS is negligible with respect to that due to CFT column made of mild steel [19].
Prototype structure with CHS (Circular Hollow Sections) columns
The use of HSS in structures subjected to strong earthquake (ag >0.25) is more complicate, because the main problem of the structure is not the element resistance but the structure deformation [19].

HITUBES PROJECT
The HITUBES project intends to develop performance-based design and assessment procedures in order to use HSS tubes in flexible structures subjected to extreme repeated loads like bridges, etc.
In order to investigate and evaluate the implementation of HSS tubular members and connections in structures subjected to extreme loadings as well as to extract realistic specimens to be tested, the following two case studies were selected.

1. A Foot-cycle bridge "Ponte del mare" in Pescara, Italy, shown in Fig. 1;
2. A railway bridge in Landegem, Belgium, illustrated in Fig.2.

The foot-cycle cable stayed bridge is mainly subjected to low cycle fatigue loading due to wind and pedestrians, whereas the railway arch bridge is subjected to high cycle fatigue loading owing to the fast passage of trains.
The main structure of the foot-cycle bridge consists of two separated curved deck supported through stayed cables to a slightly inclined mast of height of about 50 m. The cycle deck has a length of 148 m and a breadth of 4 m whilst the pedestrian deck has a length of 167 m and a breadth of 3 m. The existing footbridge, made of open sections regular steel, as shown in Fig. 3, was re-designed using circular hollow sections made of HSS TS 590 and it is depicted in Fig.4. During the redesign of the bridge, the actions on the structure were obtained from Eurocode 3, part 2.
From the analysis it resulted that the possibility of exploitation of HSS was remarkably limited from the deformability point of view. In summary, the employment of CHS provides the following advantages:

- more transparency of the bridge through the use of smaller sections with smaller inertia;
- possibility to take away the hull for aesthetic reasons, that covered the original deck of the bridge.

This should also reduce aerodynamic problems; in fact the

FIG. 1 ***Foot-cycle bridge "Ponte del Mare" in Pescara after construction.***
Ponte ciclopedonale "Ponte del Mare" a Pescara dopo la costruzione.

FIG. 2 ***Landegem railway bridge.***
Ponte ferroviario di Landegem.

actual footbridge is endowed with elastic-viscous-fluid dampers connected trough cables to the two decks in order to avoid flutter and gallopping phenomena.
- The bridge entails a lower visual impact.

The analyses made on the Landegem railway bridge demonstrate that the use of HSS is not very economical in the construction of railway bridges because the governing design criteria are fatigue in almost all structural elements. In fact, the use of HSS usually makes structural elements more slender, and then conducts to an increase of stress ranges; whereas the fatigue resistance for a detail is constant for any steel grade according to Eurocode EN 1993-1-9 [27]. Nevertheless, a post-treatment may increase the fatigue resistance for a specific detail. In

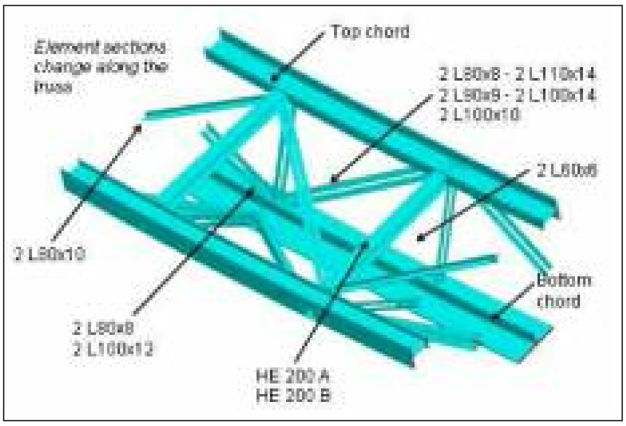

FIG. 3 ***Section of the bridge deck of "Ponte del Mare".***
Sezione della sede stradale del "Ponte del Mare".

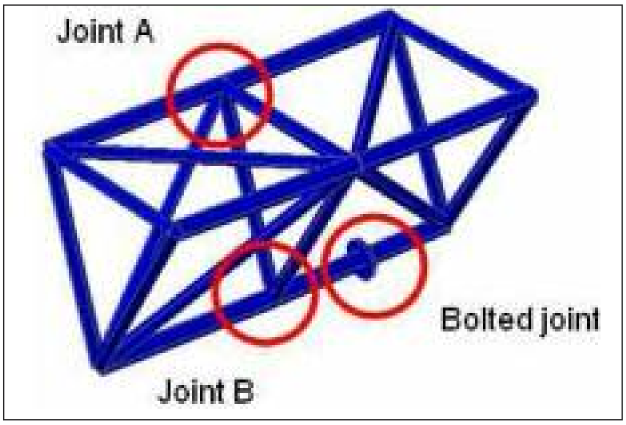

FIG. 4 ***Re-designed bridge deck with tubular sections made of HSS.***
Sede stradale del ponte riprogettata con sezioni tubolari in acciaio ad alto snervamento.

this case, the use of HSS may be economically interesting for the arches: this is one of the objectives of the project. Accordingly, the interest in using HSS for railway bridges could be reviewed on the basis of obtained experimental results in the present project.
From the deck geometry illustrated in Fig. 4, the following joints and members were extracted for tests: K and butt weld joints; X weld joints; bolted flange joints and both short and long tubular members.
As far as HSS tube provisions are concerned, the tube manufacturer Tenaris Dalmine showed interest in the project and agreed to provide the limited quantity of HSS tubes needed for physical testing. Based on the availability of HSS tubular sections from the Tenaris Dalmine's production schedule two sections, i.e. 193.7/10 and 355/12, made of TS590 were chosen. In order to do this, a compromise between design steel grades and tube dimensions was found.
The following tests are planned in the project.
1. Tests on base material: tensile test; impact test; corrosion test; strain-controlled low cycle fatigue test; fracture toughness test in order to obtain J-R curves.
2. Tests on weld material (undermatching/overmatching): impact test; hardness test; corrosion test; strain-controlled low cycle fatigue test; fracture toughness test in order to determine J-R curves; high cycle fatigue test in order to define S-N curves.
3. Tests on post-weld treatment: high cycle fatigue test as before (S-N curves) on undermatching and overmatching weld; post-weld treatment by ultrasonic peening
4. Tests on tubular members with diameter D=193.7 mm, thickness t=10 mm and made of TS 590: i) 3 full scale cyclic tests are planned on tubular members to evaluate the stability limits of large members under compressive axial and bending loading as shown in Fig. 5a,b; 1 test with cyclic axial load; 1 test with cyclic bending in the absence of axial force; 1 test with cyclic bending in the presence of axial force held constant and equal to about 50 percent of the ultimate compressive strength. The ECCS procedure for cyclic testing will be followed [28]. ii) 9 full scale monotonic tests will be performed in order to evaluate the rotational capacity of large members under compressive axial and bending loading. 4 tests with a short column configuration (tube length = 2 m) to characterize the local instability of cross-section behavior; 5 tests with long column configuration (tube length = 5 m) to characterize the global instability will be performed. The outcome of the tests will be the moment (M) – axial load (N) interaction diagram of the type shown in Fig 6: one diagram for short columns and one diagram for long columns will be created. The loading sequence to be followed is as follows: first apply the axial load N and then keeping this axial load N constant; then apply bending moment M up to tube failure.
5. Tests on X welded joints: This experimental study consists of 10 tests on welded X-joint specimens. The main purpose of these tests is the examination of the mechanical behaviour of HSS (TS590) welded X-joint specimens under cyclic

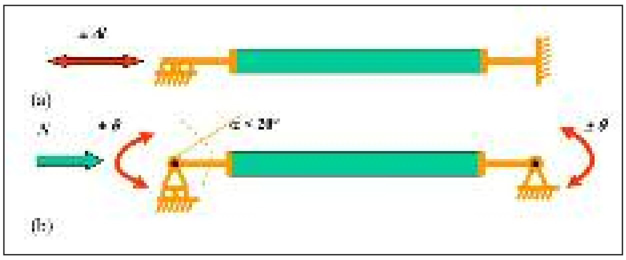

FIG. 5 ***Full scale cyclic column tests. Details of boundary conditions and load configurations.***
Test ciclici su colonne in vera grandezza. Dettagli delle condizioni di vincolo e tipologie di carico.

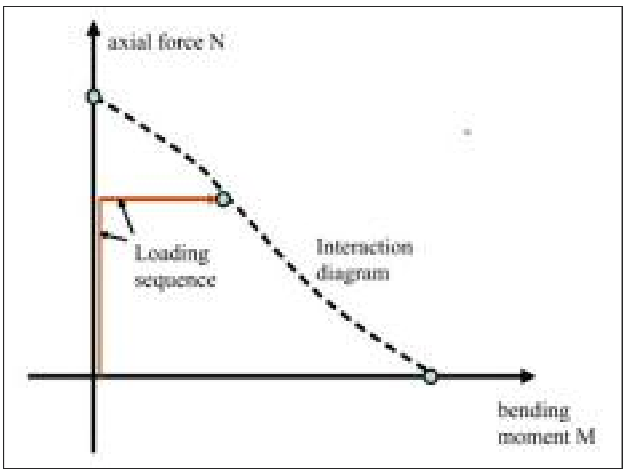

FIG. 6 ***Interaction diagram and loading sequence for member tests under monotonic loading.***
Diagramma di interazione e sequenza di carico per prove sugli elementi sotto carichi monotonici.

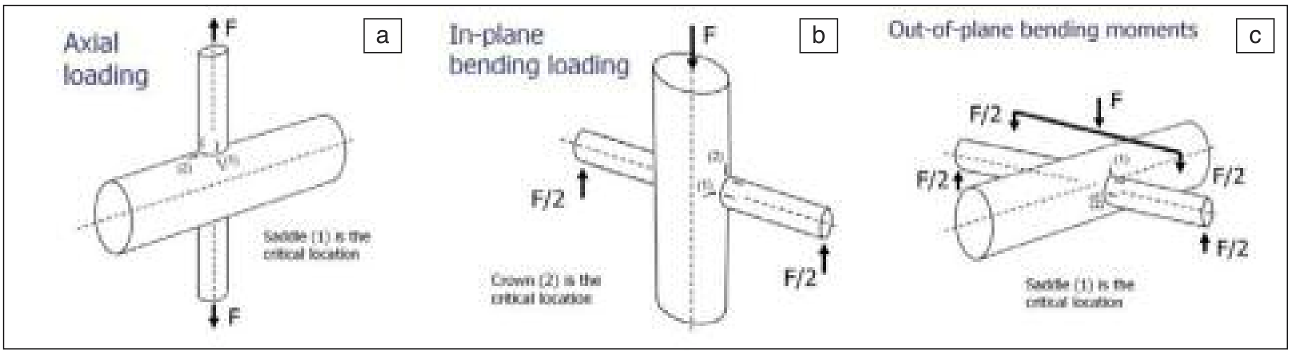

FIG. 7 ***(a) Axial loading.*** ***(b) In-plane bending loading.*** ***(c) Out-of-plane bending loading.***

(a) Carico assiale. *(b) Carico. flessionale nel piano.* *(c) Carico flessionale fuori dal piano.*

loading (low-cycle fatigue) and monotonic loading. The specimens will be subjected to balanced axial force (AF), in-plane bending (IPB) and out-of-plane bending (OPB) loading, according to Fig. 7. For each type of bending loading (IPB and OPB) two specimens will be tested under low-cycle fatigue cyclic loading and two specimens under monotonic loading. Also two specimens will be tested under axial cyclic loading in low-cycle fatigue regime. Furthermore, out of the total ten specimens, five will be with overmatched and five will be composed of undermatched weld. With regard to the fatigue tests, the loading ratio R and the loading frequency f will be 0.1 and 1 Hz, respectively.

6. Tests on bolted flange joints on tubes with diameter D=193.7 mm, thickness t=10 mm, made of TS 590: a total of 6 tests is planned. Two different flange configurations, see Table 4, are chosen in order to form Mode 1 and Mode 2 plastic mechanisms [29]. Three types of loading conditions are applied: monotonic loading; low-cycle fatigue loading; high cycle fatigue loading. The applied axial force is designed such as in the LCF tests; each specimen can reach fatigue failure at about 200-300 cycles whilst in the HCF tests each specimen can reach fatigue failure at about 2x106 cycles at 1.0 Hz.

Data from material tests will be helpful to perform tests on members, on welded and bolted connections and numerical simulations. Numerical simulation of the overall case studies with improved design will be made and recommendations will be issued.

MIS-MATCHING WELD AND ELECTRODE SELECTION

The weld joints were designed according to Eurocode 3 part 1-8. We realized that Eurocodes are not sufficient to design welds and weld profiles; hence we also followed the guidelines of the American Welding Society (AWS) code for this task [30].

The typology of weld i.e. undermatching or overmatching was not so clear for HSS welded connections. HSS materials exhibit higher yield and tensile strengths. Many authors [8, 31] suggest an undermatching weld in the case of HSS. In the case of HSS Miller strongly suggests undermatching welds for HSS, because residual stresses are assumed to be of the order of the yield point of the weaker material in the joint. This is very important for crack initiation under HCF loading. Johansson suggests undermatching welds too [8]. Many other authors [32, 33], suggest overmatching welds, in order to achieve sufficient deformation capacity. They indicate the use of weld reinforcement with undermatching, if overmatched electrodes are not available for very high strength steels, e.g. S1100. They conclude that overmatched welded joints in S690 have a good strength and deformation capacity. In general the ratcheting tests on welded joints made of S690 nearly provide the same results with respect to strength and deformation capacity as static load tests.

A paper based on experiments [34] favours overmatching in the case of high-cycle fatigue loading. Due to the lack of a clear understanding about the types of welding, i.e. undermatching or overmatching applied to HSS materials, in order to get more insight in this issue; we take the opportunity to test both types of weld specimens in this project.

The preliminary tensile tests carried out by Tenaris Dalmine on the coupons extracted from the manufactured tube (TS590, D/t=193.7/10) indicate very high yield strength than that stated in the Tenaris material catalogue. Test results are shown in Table 5.

The nominal minimum yield strength present in the catalogue was 590 MPa, but the tests on coupons show higher yield strength. The mean yield strength is about 694 MPa. Hence, we chose weld electrodes based on actual strengths as obtained from tests and not from nominal values [35].

Table 6 reports the electrodes chosen in the course of the HITUBES project.

CONCLUSIONS

The application of tubular members and joints made of high strength steel is very promising in civil engineering. It is expected that when properly applied high strength steel Grade TS 590 can exhibit significant opportunities for cost and weight savings in addition to aesthetic benefit. Nonetheless, the practical exploitation of HSS Grade TS 590 for bridges and building structures requires a careful attention to both design and fabrication details. Along these lines, the two European projects

TAB. 4
Flange joint configuration.

Configurazione del giunto flangiato.

	1st configuration	2nd configuration
Design static resistance	1142 kN	1354 kN
Tubes	D355/12, S590	D355/12, S590
Bending flange plates	D555/15, S355	D555/20, S355
Bolts	12M27, grade 8.8	12M20, grade 8.8
Tensile plates	900 mm/435 mm/20 mm, S355	900 mm/435 mm/20 mm, S355

TAB. 5
Result of the tensile tests on coupons from 193.7/10 tube of TS590.
Risultato delle prove di trazione su provini da tubo 193.7/10 in TS590.

No. of samples	Yield Str. (YS)	Tens. Str. (TS)	YS (mean)	TS (mean)	Elongation
6	616-765	702-822	694	770	>16%

TAB. 6
Weld-electrodes.
Elettrodi per saldatura.

Weld Type	Electrode Class [36]	YS (min)	TS	S_{ye}/S_{yb} TS590 S_{yb}=694	S_{ye}/S_{yb} S355 (S_{yb}=355)
Undermatching to TS590	55	550	640-820	0.79	-
Overmatching to TS590	79	790	880-1080	1.14	-
Undermatching to TS590 and Over-matching to S355	46	460	530-680	0.66	1.30

Note: S_{ye} = yield strength of the electrode and S_{yb} = yield strength of the base metal.

ATTEL and HITUBES will shed more light on these issues.

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Abstract

Colonne circolari e connessioni in acciaio ad alto snervamento sottoposte a carichi sismici, di incendio e a fatica

Parole chiave: acciaio, saldatura, simulazione numerica, norme e statistiche, tecnologie

L'acciaio ad alta resistenza è disponibile ormai da parecchi anni. Ciononostante, il suo utilizzo in applicazioni civili è abbastanza restrittivo. Una ragione è che le normative strutturali e gli Eurocodici hanno coperto gli acciai ad alto snervamento fino ai 460 MPa; l'altra ragione è costituita dai maggiori costi rispetto agli acciai standard. Nonostante questo, recentemente c'è stata una crescita costante dell'uso di acciai ad alta resistenza in strutture tubolari grazie all'Eurocodice 3 Parte 1-12 (2006), che ha esteso la propria validità per gradi di acciaio fino a S690/S700MC. L'Eurocodice 3 Parte 1-12 impone però molte limitazioni a livello di materiali, progetto e calcoli strutturali.
Gli ambiziosi obiettivi dei due progetti finanziati dalla Comunità Europea – ATTEL e HITUBES – sono stati quelli di incrementare le prestazioni di strutture tubolari, riducendone peso, costi di costruzione e di esercizio.
Entrando nel dettaglio, lo scopo del progetto ATTEL è quello di promuovere l'uso di elementi in acciaio ad alta resistenza con profili a sezione circolare cava in edifici soggetti a terremoti e incendio, in modo da capire il comportamento dell'acciaio ad alto snervamento rispetto a quello standard.
Pertanto, sono stati considerati diversi edifici soggetti a carichi statici, a sismi di media (<0.25g) e alta intensità (>0.25g). E' stato inoltre considerato il carico da incendio, anche se come azione indipendente rispetto al sisma.
Gli edifici sono stati realizzati con acciaio TS590 per i pilastri ed S275 per le travi, in modo da soddisfare i criteri di gerarchia delle resistenze (o capacity design) per travi e pilastri sotto carichi sismici. Il progetto preliminare di queste strutture ha portato alle due seguenti conclusioni: i) i benefici in termini di costo per l'uso di pilastri in acciaio ad alto snervamento in telai controventati, soggetti principalmente a carichi assiali e bassi momenti flettenti; ii) benefici in termini di costo, relativamente all'uso di pilastri in acciaio ad alta resistenza in telai non controventati, ottenuti solo lungo la direzione principale e per carichi sismici di media intensità (<0.25g).
Test fisici su modelli a grandezza naturale di giunti trave-pilastro e sui nodi inferiori dei pilastri verranno condotti all'Università di Trento e consentiranno di verificare ulteriori dettagli per questi importanti componenti.
Per quanto riguarda il progetto HITUBES, il lavoro principale riguarda elementi e nodi soggetti a carichi monotoni a basso e ad alto numero di cicli. In particolare, il progetto si è focalizzato su: i) estrazione di collegamenti saldati e bullonati da due casi di studio, rispettivamente una passerella pedonale e un ponte ferroviario; ii) definizione di una Welding Procedure Specification (specifica di procedimento di saldatura) – overmatching e undermatching – e trattamenti post-saldatura – peening – per collegamenti tubolari saldati; iii) preparazione di disegni per campioni e protocolli per i test.