The EQUALJOINTS project:
European pre-qualification of steel joints

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1. ABSTRACT

The design of beam-to-column joints for seismic applications is not properly addressed in current version of Eurocodes. EN 1998-1 allows using dissipative beam-to-column joints in seismic resistant steel frames. However, due to the lack of analytical tools able to predict the seismic performance of such connections the EN 1998-1 prescribes design supported by testing, resulting in an expensive and time-consuming approach. On the other hand, also for full-strength joints reliable design tools are necessary because, owing to the variability of steel strength, these connections could not have enough overstrength and the plastic rotation capacity of the joint assembly must be prequalified by relevant tests. In order to overcome such limitations, the aim of Equaljoints project was to develop a prequalification procedure for typical joints used in the EU practice, on the basis of experimental, numerical and analytical investigations. Design tools and prequalification charts are provided, including general requirements, limitations, step-by-step design procedure and qualification data.

2. INTRODUCTION

Nowadays, prequalification criteria for steel beam-to-column joints in seismic resistant systems are currently missing in Eurocodes. Even though several experimental and analytical studies are available, none was specifically addressed to select and prequalify European seismic-resistant joints on the basis of parametric experimental and numerical investigations. On the contrary, in USA prequalified seismic resistant joints are common practice, with codified design procedure and reliable and easy-to-use design tools. After the Northridge earthquake, the US research efforts were addressed to prequalify a set of selected joint types to be used in both special and intermediate moment resisting frames. Since 1995, US FEMA and SAC joint venture developed a six-years research project (the FEMA/SAC program) devoted to provide guidelines for seismic design of steel moment resisting steel frames, including codified criteria for inspection, evaluation, repair, rehabilitation, and construction of steel moment frame resisting structures. The results arisen within the FEMA/SAC program were directed to feed into a specific standard (ANSI/AISC 358-05 [1]) containing design, detailing, fabrication and quality criteria for the set of prequalified typologies, which includes the most common configurations of joints used in the US practice, e.g. welded-flange-bolted-web connections, haunched and cover-plated connections, bolted T-stub connections, and double-flange-angle connections. Seismic prequalification activity was also successfully accomplished in Japan, were columns are usually made of cold formed steel tubes with shop weld placed at a short distance away from the face of the column. Connection details with bolted webs and field-welded flanges are also used with built-up box columns. Unfortunately, joint typologies and shape and properties of members, bolts and welds commonly used in US and Japanese practices, are different from those typically used in Europe.

At the current stage, EN 1998-1 [2] allows using dissipative beam-to-column connection, but it prescribes design supported by experimental testing, which results in impractical solutions within the time and budget constraints of real-life projects. On the other hand, no design tools to reliable predict the plastic rotation capacity of non-dissipative (namely full strength) joints are available. Indeed, owing to the variability of steel strength, these connections could not have enough overstrength (e.g. min 1.1×1.25 $M_{b.rd}$, being $M_{b.rd}$ the bending strength of the beam), and in such cases their plastic rotation capacity must be prequalified by relevant test and numerically based procedures. Moreover, it should be noted that the European seismic input differs from US earthquake, also affecting the ductility demand at both global and local level and thus furtherly limiting the application of US prequalification to the European practice. In the light of these considerations, “Equaljoints” project was aimed at providing European qualification of beam-to-column joints for seismic application, focusing on the standardization of design and manufacturing procedures with reference to a set of selected joint configurations (see Fig. 1), namely bolted haunched joints, bolted extended stiffened end-plate joint, bolted extended unstiffened end-plate joint and welded dog-bone joint, which were designed to provide two performance levels: rigid full strength, for severe seismic zones and semi-rigid partial strength for medium-to-severe seismic zones. The research activity developed within the project was characterized as pre-normative research intended to develop design tools and prequalification charts to be included in the next version of EN 1998-1. In detail, the EQUALJOINTS project has threefold objectives, which can be summarized as follows:

1. To provide codified seismic pre-qualification charts for a set of steel standard joints, thus aiming to propose relevant criteria for the next version of EN 1998-1 [2];
2. To develop analytical and numerical models for predicting the behaviour of beam-to-column joints under cyclic loading, on the basis of a wide experimental campaign;
3. To define technological requirements for fabrication of standardized steel joints and to evaluate the economic benefits related to the costs and constructional time of different solutions.

These objectives were achieved by performing a comprehensive experimental program as well as theoretical and numerical analyses. The present paper provides an overview of the project and the main results are described and discussed.

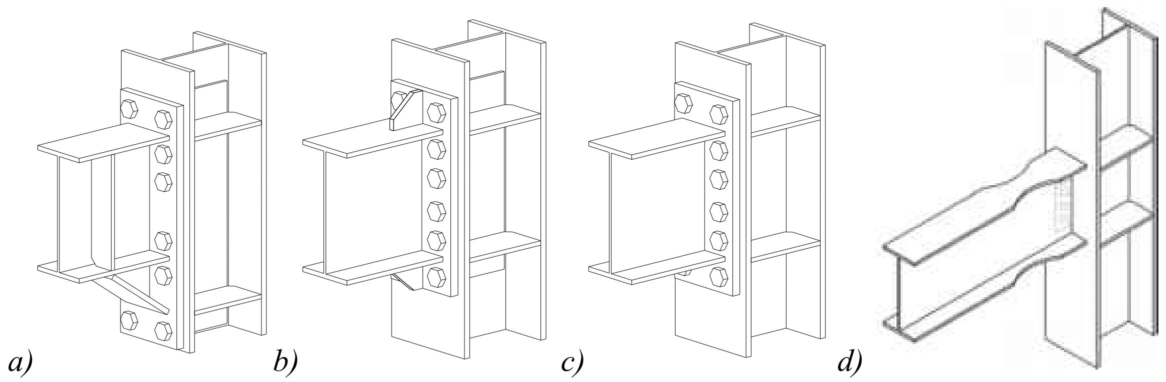


Fig. 1: Beam-to-column joints investigated in the framework of EQUALJOINTS project: a) Bolted haunched joints b) Bolted extended stiffened endplate joint c) Bolted extended unstiffened endplate joint d) Welded dog-bone joint

3. PARTNERSHIP OF THE PROJECT

The research group includes both European academic institutions and companies, i.e. five universities, the European association of steel fabricators, and a steel producer. In detail, the partners and the relative responsible people are indicated in the following:

- University of Naples Federico II – UNINA (R. Landolfo, project coordinator)
- Imperial College – IC (A. Elghazouli)
- University of Coimbra- UC (L. da SILVA)
- University of Liege – ULG (J.P. Jaspart)
- Universitatea "Politehnica" din Timisoara – UPT (D. Dubina)
- The European Convention for Constructional Steelwork - ECCS, (V. Dehan)
- ArcelorMittal Belval & Differdange S.A. (O. Vassart)

4. RESEARCH PROGRAM

The research program is divided in four main parts, which are numerical investigations, experimental tests, analytical models and development of design recommendations (see Fig. 2).

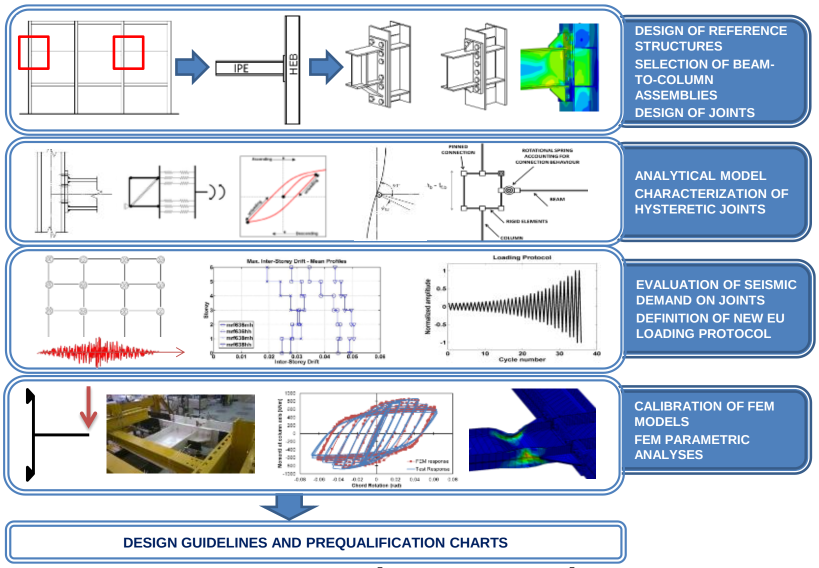


Fig. 2: Equaljoints action plan

In order to achieve the goals of the projects, the research program was formulated in the following working packages (WP):

- WP1 (leader: IC-Elghazouli) - Selection and design of joint typologies

This WP is devoted to select and design the joint configurations to be qualified, in order to be representative of most commonly typologies implemented in the seismic resistant steel frames in Europe. With this aim, the dimensions of connected members were obtained from design calculations of both moment resisting and dual systems according to EN 1998-1 [2]. The design of joints for the selected beam-to-column assemblies was developed after a critical review of the existing design and analytical methods and constantly supported by FE simulations. In addition, a new loading protocol representative of European seismic demand was developed. To this aim, a comprehensive set of non-linear time-history analyses was performed considering two sets of ground motions scaled to match the EC8 spectra.

- WP2 (leader: UC-Da Silva) - Analytical Models

Analytical tools able to predict and characterize the seismic behaviour of selected beam-to-column joint types were developed within WP2. In particular, the component method was extended to the case of cyclic loading in order to obtain design tools for the prediction of the inelastic cyclic performance of partial strength dissipative joints.

- WP3 (leader: UNINA-Landolfo) - Numerical Tests

The research activity of WP3 focused on finite element simulations. At the first stage of the project the finite element analyses supported the design of joint specimens and the test setups.

Subsequently, finite element analyses (FEAs) were performed both before and after the execution of experimental tests in order to investigate the key parameters affecting the joint response. In the post-experimental phase, the numerical models were calibrated on the basis of experimental results. Afterwards, on the basis of validated numerical models a parametric study is carried out in order to extend the research outcomes to a wider range of geometrical and mechanical variations per joint.

- WP4 (leader: UPT-Dubina): Experimental Tests

The WP4 was devoted to perform tests on the steel joints selected and designed within WP1. Experimental tests were performed in order to demonstrate both the effectiveness and the reliability of the designed joint detailing under seismic/wind simulated loading. In WP4 the failure criteria were defined per limit state.

- WP5 (leader: ULg-Jaspart): Design tools

The main aim of WP5 was to collect and to organize results coming from WP2, WP3 and WP4 activities, in order to develop design guidelines, including the recommended details of each investigated joint typology, the design methodology and relevant design criteria.

- WP6 (leader: UNINA-Landolfo): Coordination, management and dissemination

WP6 was devoted to managing, coordinating and disseminating the research activities. At the end of the project an International workshop was organized in Napoli (Italy) on 21 June 2016. The main results achieved by this project were also presented and discussed for first time within that event. In addition, three invited keynote speakers gave interesting contributions to the discussion. In particular, Prof. R.T. Leon (Virginia Tech) showed the prequalification and design criteria of seismic resistant steel joints in USA. Prof. M. Veljković (University of Delft) showed how making EN 1993-1-8 easier to use. Prof. V. Piluso (University of Salerno) showed seismic design criteria of bolted beam-to-column joints.

5. DESIGN CRITERIA

The design criteria developed within the project aim at harmonizing the requirements of hierarchy of resistances of the macro-components of the joint (e.g. the web panel, the connection, the beam and the column as shown in Fig. 3), and their sub-components (e.g. end-plate, bolts, welds, etc.), as well.
Each macro-component is individually designed according to specific assumptions and then simply capacity design criteria are applied in order to obtain three different design objectives defined comparing the joint (i.e. web panel and connection) strength to the beam flexural resistance, namely (i) full strength, (ii) equal strength and (iii) partial strength joints [5].

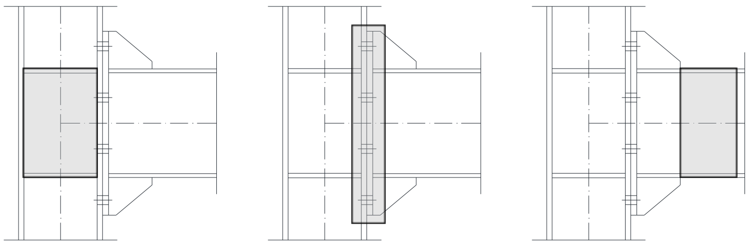


Fig. 3: Plastic regions of the joints: a) web panel, b) connection and c) beam.

Both Full and Equal strength joints are intended for applications in MRFs, depending on the level of design ductility class namely the first for DCH and the second for DCM, respectively. Partial strength joints can be used for Dual braced frames (e.g. MRF+CBF and MRF+EBF), where the moment resisting parts of the structure are designed to resist about 25% of base shear (e.g. as recommended by AISC341) and the MRF spans should mostly provide redundancy and plastic distribution of seismic shear forces along the building height, in order to limiting the tendency to soft storey mechanism that typically affects braced structures.
Full strength joints are designed to guarantee the formation of all plastic deformations into the beam, which is consistent with EC8 strong column-weak beam capacity design rules. Equal strength joints are theoretically characterized by the contemporary yielding of all macro-components (i.e. connection, web panel and beam). Partial strength joints are designed to develop the plastic deformation only in the joint.
It should be also noted that both EC3 and EC8 do not consider the case of equal strength joint, which is proposed in this study as an intermediate performance level. According to the current Eurocode classification, an equal strength joint falls on the category of partial strength.
The capacity design requirements to obtain the required joint behaviour can be expressed by the following inequality [5]:

$$M_{wp,Rd} \geq M_{\mathrm{j},Rd} \geq M_{\mathrm{j,E}d} = \alpha \cdot (M_{\mathrm{B},Rd} + V_{B,Ed} \cdot s_h) \qquad (1)$$

Where $M_{\mathrm{wp,Rd}}$ is the flexural resistance corresponding to the strength of column web panel; $M_{\mathrm{j,Rd}}$ is the flexural strength of the connection; $M_{\mathrm{j,Ed}}$ is the design bending moment at the column face; α depends on the design performance level. It is equal to $\gamma_{\mathrm{sh}} \cdot \gamma_{\mathrm{ov}}$ for the full strength joints (being γ_{ov} the overstrength factor due to the material randomness, and γ_{sh} the strain hardening factor corresponding to the ratio between the ultimate and the plastic moment of the beam), while equal to 1 for equal strength joints and smaller than 1 for partial strength joints. A lower bound of α was set equal to 0.8 in order to avoid damage concentration in the connection zone. $M_{B,Rd}$ is the plastic flexural strength of the connected beam; s_h is the distance between the column face and the tip of the rib stiffener; $V_{B,Ed}$ is the shear force corresponding to the occurring of the plastic hinge in the connected beam; it is given by:

$$V_{B,Ed} = V_{B,Ed,M} + V_{B,Ed,G} \tag{2}$$

where $V_{B,Ed,M}$ is the shear force due to the formation of plastic hinges at both beam ends, spaced by the length L_h and calculated as:

$$V_{B,Ed,M} = \frac{2 \cdot M_{B,Rd}}{L_h} \tag{3}$$

$V_{B,Ed,G}$ is the contribution due to the gravity loads; L_h is the approximate distance between plastic hinges.

6. EXPERIMENTAL ACTIVITY

The experimental program (summarized in Table 1) includes 76 beam-to-column specimens by varying the joint typologies, the performance objectives, the joint configuration (internal/external joints), and the loading protocol (monotonic and two different cyclic loading protocols are used).
It should be noted that the performance level “Equal strength” is not codified in EN 1993-8 [2]. It was defined within the Equaljoints project as intermediate performance objective. In this type of joint plastic deformation are expected to contemporarily occur in both beam and connection zones. The experimental campaign was also devoted to characterize the monotonic and cyclic properties of European steel grades. Therefore, monotonic and cyclic coupon tests as well as Charpy tests were carried out to characterize the inelastic properties of the material. In addition, tests on high-strength prelodable bolts were carried out to investigate the axial performance of both European HR and HV bolt assemblies [4].

Parameter	Variation
Beam to column assembly	Small beam (IPE 260) – Medium beam (IPE450) – Deep Beam (IPE600) *Dogbone designed for W-type US profiles
Joint type	Haunched – Extended stiffened endplate – Extended unstiffened endplate - Dogbone
Joint configuration	Internal/External
Performance objective	Full strength – Equal strength – Partial strength
Loading protocol	Monotonic – Cyclic AISC – Cyclic Proposed EU protocol
Shot Peening	Yes/No

Table 1: Experimental program.

Figure 4 shows the experimental results performed on an external full strength extended stiffened end-plate joint connecting IPE 450 beam with HEB 340 column. The response curve is expressed in terms of moment at column centreline vs chord rotation. As it can be noted, plastic deformation actually occurred into the beam only, thus satisfying the strength hierarchy requirement “strong column-weak beam”. The response curve shows stable hysteretic behaviour indicating good energy dissipation.
Figure 5 shows the experimental response of an equal strength extended stiffened end-plate joint connecting IPE 360 beam with HEB 240 column. Also in this case the experimental evidence confirms the effectiveness of the design assumptions. Indeed, plastic deformation actually occurred in the end-plate and the beam flange; no yielding phenomena are recognized in the column web panel zone.
Figure 6 shows the experimental results for the same beam-to-column assemblies connected by an internal equal strength unstiffened extended endplate joint. In this case the column web panel was designed to be “balanced” respect to the connection zone and plastic deformations are mainly concentrated in these zones; also the beam flange experiences yielding phenomena without buckling.
The experimental results in terms of cyclic response curve and failure mode of a dog-bone joint are reported in Figure 7. In this case the column web panel was designed to be “strong” respect to the plastic resistance of the reduced beam zone as confirmed by the experimental behaviour.
It should be noted that all specimens satisfy the qualification limits given by both AISC 341-16 [3], namely 4% interstorey drift angle with corresponding strength larger than 80% the plastic bending strength.

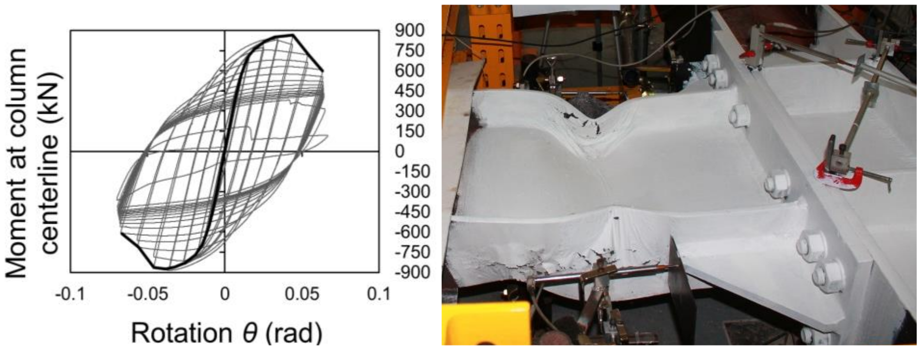


Fig. 4: Moment-rotation behaviour of equal strength stiffened extended endplate joint tested in UNINA lab: plastic deformation contemporarily occurring in connection zone and beam flange.

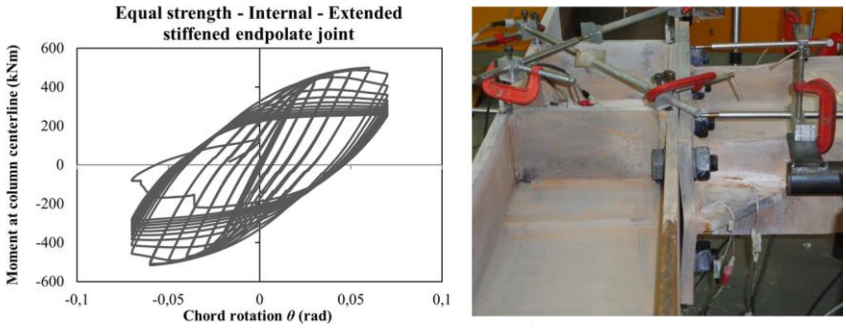


Fig. 5: Moment-rotation behaviour of equal strength extended stiffened end-plate joint tested in UNINA lab: plastic deformation contemporarily occurring in connection zone and beam flange.

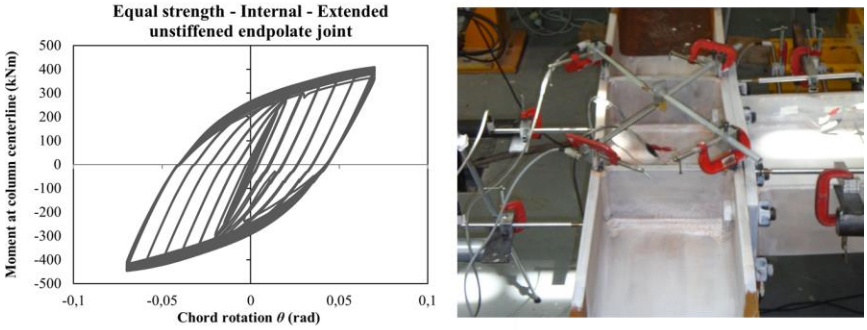


Fig. 6: Moment-rotation behaviour of extended unstiffened end-plate equal strength joint tested in UNINA lab: plastic deformation contemporarily occurring in column web panel zone, connection zone and beam flange.

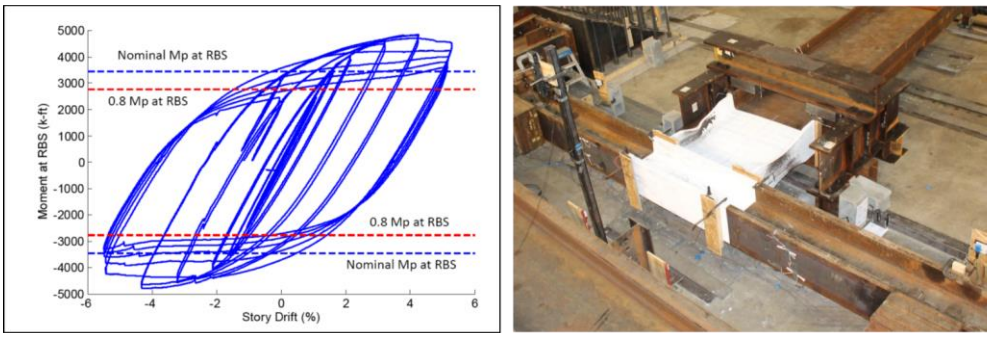


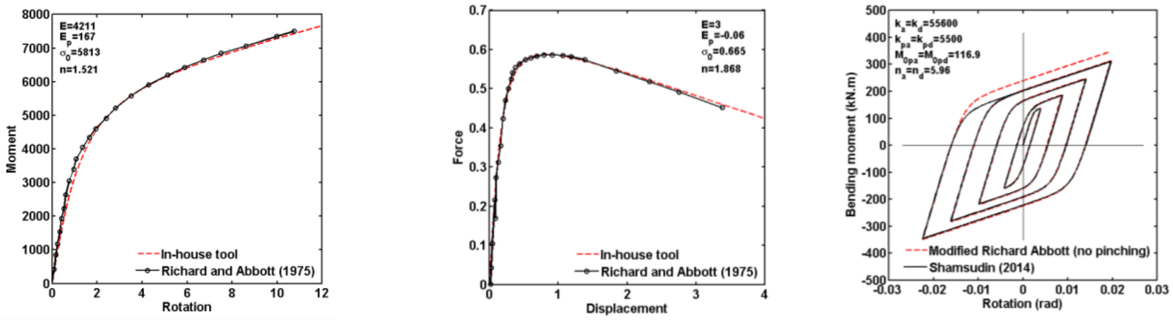
Fig. 7: Moment-rotation behaviour of dog-bone joint tested in Virginia Tech lab: plastic deformation contemporarily occurring in the reduced beam zone.

7. ANALYTICAL MODELS OF CYCLIC RESPONSE OF JOINTS

The component methods implemented by Eurocode 3 [6] allows predicting the joints monotonic moment-rotation behaviour for a wide range of joint configurations, but EC3 [6] does not provide analytical tools for cyclic actions.

Within the research activity of Equaljoints project, the component method was critically revised and extended to the cyclic response of the joints. In order to achieve this objective, the cyclic behaviour of mechanical components was investigated on the basis of literature and finite element analyses and the relevant hysteretic response curves were determined.

The mathematical equations of “Modified Richard Abbott method” [7] were used to generate component behaviour. An in-house tool has been developed by implementing above expressions. This tool can be accessed from Matlab File Exchange. Figure 8 shows capability to simulate the response of extended end-plate connection by using Richard-Abbott [8] tool for approximating moment-rotation relationship with hardening and force-displacement and also for approximating hysteretic moment-rotation as given by Shamsudin [9].



(a) Moment-rotation with strain hardening

b) Force-displacement with strain softening

c) Moment vs rotation of extended end-plate joint

Fig. 8: Developed Modified Richard Abbott model vs. experimental results.

8. LOADING PROTOCOLS FOR EUROPEAN QUALIFICATION

Within the project, a new loading protocol representative of European seismic demand was developed for the prequalification of beam-to-column joints. In order to define the European loading protocol a comprehensive set of nonlinear time history analyses were performed on reference structures designed within WP1. Two ensembles of European ground motions, one representative of high seismicity and another representative of medium seismicity were used to simulate the seismic action.

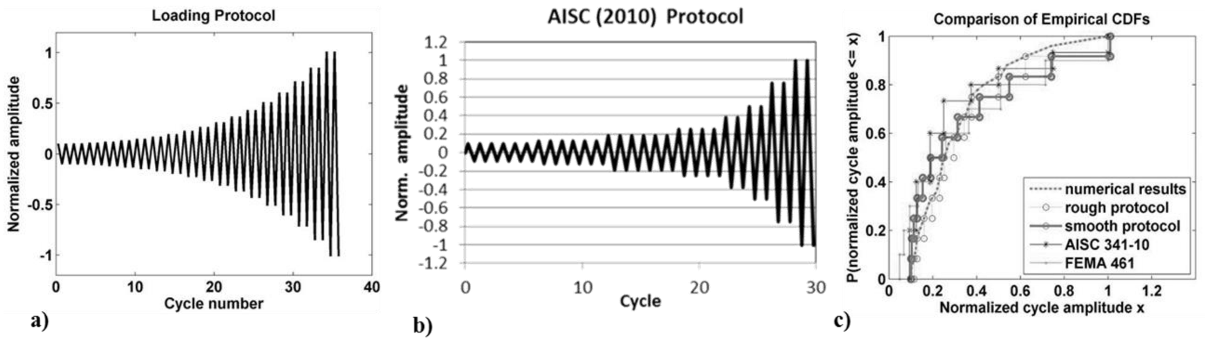


Fig. 9: Derived loading protocol (a) AISC 2010 loading protocol (b) comparison of CDF (c)

Refined numerical models of frames were used to investigate the seismic performance, specifically accounting for cyclic response of the selected joints. Cumulative and maximum rotation demands obtained from the analyses provided the basis for the selection of the protocol in order to represent more accurately design earthquake demands. The basis of the adopted methodology has been presented by [10] as part of the SAC project research after the 1994 Northridge earthquake. More recently, a set of cyclic loading protocols for European regions of low to moderate seismicity has been developed by [11] on the basis of nonlinear time-history analyses of a set of single-degree-of-freedom systems, corresponding to various types of structural systems. The latter methodology by [11], with appropriate adaptations, was used within EQUALJOINTS project. For the ground motion set corresponding to each case, median sequences of normalized amplitudes were derived and subsequently used for constructing a loading protocol representative of the drift demands at each seismicity level. The input signals were extracted from the storeys that sustained the maximum inter-storey drifts, for each frame typology. The analyses were carried out using OPENSEES [12]. The selected drift response histories correspond to a seismic intensity level consistent with the near collapse (NC) limit state, as a minimum. The derived median loading protocols is presented in Fig. 9a, compared with those provided for by AISC 341 [3] (see Fig 9b). Moreover comparative plots of the respective cumulative ductility functions are shown (CDF) in Fig. 9c.

9. FEM SIMULATIONS

All experimental tests were simulated by means of finite element analyses. Moreover, parametric numerical analyses were carried out on the basis of models validated against experimental results, in order to extend test outcomes and to deepen the knowledge of the behaviour of examined typologies of joints (see Fig. 10). With this regard, the number of cases to be numerically investigated was increased by varying both geometrical and mechanical variables which may affect the joint performance, namely he beam depth–to-column depth ratio, beam flange slenderness, beam width, column flange slenderness, dimension and shape of stiffeners have been varied. In addition, the influence of design criteria, the number of bolt rows, the yield strength of base materials have been varied with respect to the base model.

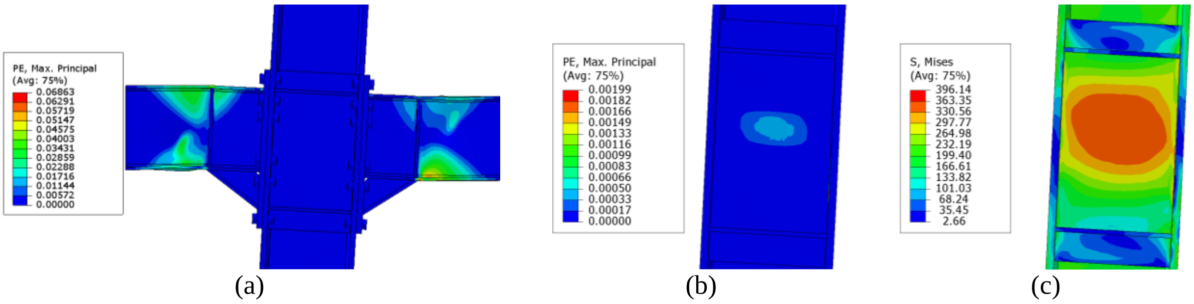


Fig. 10: Parametric numerical simulations. a) plastic strain in joint, (b) plastic strain in panel zone, (c) Mises stress in panel zone at ultimate strength of the joint

10. DATABASE OF EXPERIMENTAL TESTS ON SEISMIC RESISTANT JOINTS

Experimental and numerical data were collected by all partners into a database application developed to manage a wide range of data. In this database all the available recorded data including the organization and source of the data, geometric properties of each element, material properties of each element, geometrical imperfection if available, loading protocols, hysteretic behaviour of joints, failure modes are reported. Figure 11 shows the main graphical user interface of the developed by UC.

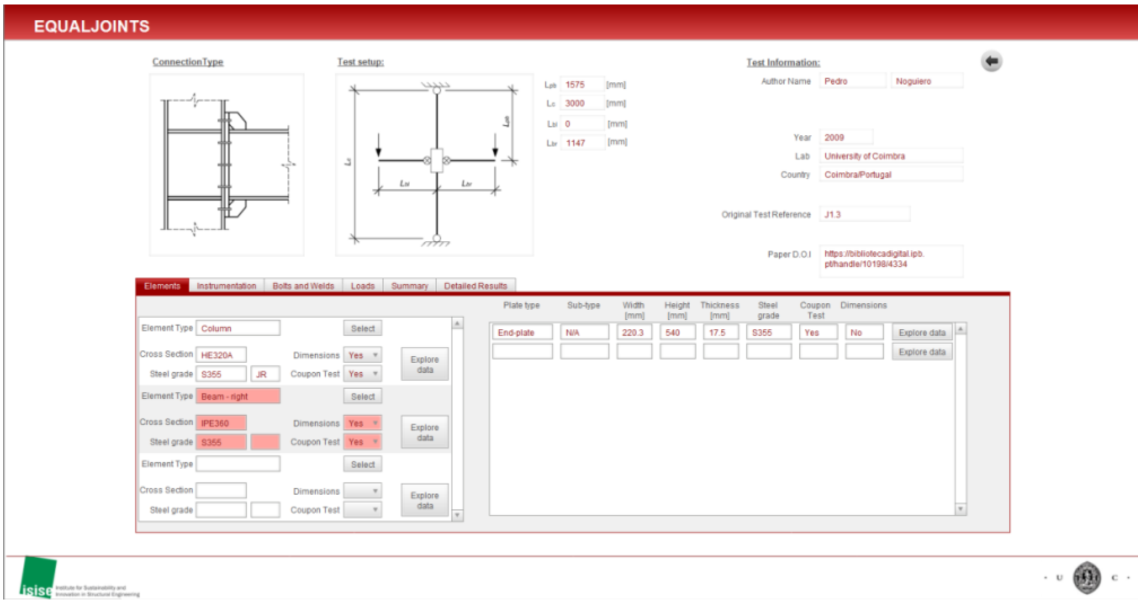


Fig. 11: GUI of database application.

11. CONCLUSION

An overview of the recently completed European research project “Equaljoints (European pre-QUALified steel JOINTS, RFSR-CT-2013-00021) has been provided. On the basis of an extensive experimental campaign and comprehensive numerical and analytical analyses, the project was devoted to introduce in European practice a pre-qualification procedure for the design of moment resisting connection in seismic resistant steel frames, in compliance with EN1998-1 requirements. It was also intended as a pre-normative research aimed at proposing relevant design criteria to be included in the next version of EN 1998-1.

12. REFERENCES

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Το ευρωπαϊκό πρόγραμμα EQUALJOINTS πιστοποιημένων μεταλλικών συνδέσεων

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ΠΕΡΙΛΗΨΗ

Ο σχεδιασμός συνδέσεων δοκών-υποστυλωμάτων για αντισεισμικές εφαρμογές δεν αντιμετωπίζεται ικανοποιητικά με τις τρέχουσες εκδόσεις των Ευρωκωδίκων. Για παράδειγμα, το κείμενο του EN 1998-1 επιτρέπει τη χρήση συνδέσεων δοκών - υποστυλωμάτων σε περιοχές απορρόφησης ενέργειας σε πλαίσιωτές κατασκευές. Ωστόσο, λόγω της έλλειψης αναλυτικών εργαλείων ικανών να προβλέψουν την σεισμική απόκριση τέτοιων συνδέσεων, το πρότυπο EN 1998-1 προβλέπει την υποστηριζόμενη από δοκιμές διαδικασία σχεδιασμού, με αποτέλεσμα μια δαπανηρή και χρονοβόρα προσέγγιση.
Από την άλλη πλευρά, είναι απαραίτητα αξιόπιστα εργαλεία σχεδιασμού ακόμη και συνδέσεις πλήρους αντοχής, καθώς λόγω της μεταβλητότητας των αντοχών των χαλύβων υπάρχει η περίπτωση οι συνδέσεις αυτές να μην έχουν την απαιτούμενη υπεραντοχή. Τέλος, η στροφική ικανότητα των συνδέσεων πρέπει να πιστοποιείται μέσω σχετικών πειραματικών δοκιμών. Προκειμένου να ξεπεραστούν οι παραπάνω περιορισμοί, το Ευρωπαϊκό πρόγραμμα EQUALJOINTS έχει ως στόχο την πιστοποίηση των σχετικών διαδικασιών σχεδιασμού για τυπικές συνδέσεις δοκών-υποστυλωμάτων που χρησιμοποιούνται στην ευρωπαϊκή πρακτική των μεταλλικών κατασκευών. Προβλέπεται η σύνταξη εργαλείων σχεδιασμού και διαγραμμάτων πιστοποιημένων χαρακτηριστικών. Ακόμη, στα παραδοτέα του προγράμματος περιλαμβάνονται η περιγραφή των γενικών απαιτήσεων και των περιορισμών. και η βήμα-προς-βήμα διαδικασία σχεδιασμού και η πιστοποίηση των δεδομένων.