Modelling of the Dissipative Behaviour of Partial-Strength Beam-to-Column Steel Connections

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LISBOA 2012

SUMMARY:
Seismic design is quickly evolving to the adoption of performance-based procedures focusing largely on deformation control. This requires a good understanding of the nonlinear behaviour of structural components. In the case of steel structures composed by moment-resisting frames, the inelastic behaviour is expected to develop mostly through flexural hinging of the beams and/or through plastic deformation of partial-strength beam-to-column connections. This paper presents a study focused on the development of FE models for reliable representation of the cyclic behaviour of partial-strength bolted steel beam-to-column connections, particularly end-plate connections. The results obtained can be directly applied in the derivation of input parameters used in the direct displacement-based design procedure. Moreover, they can be also employed in the development of cyclic component-based models.

Keywords: Connections, Steel, Cyclic, FE modelling, DDBD method

1. INTRODUCTION

Earthquakes are one of the most devastating natural disasters in the planet, usually leading to a high economic impact and endangering a great number of lives, due to the severe damages on buildings and equipments. The studies presented in this paper intend to contribute to a better understanding of the seismic behaviour of steel framed structures taking into account the real behaviour of steel joints in the structural analysis and design process.

The behaviour of steel frames is strongly influenced by the behaviour of their connections, and as such the deformation inflicted by an earthquake is also influenced by them. Since the deformations / displacements are the main responsible for the potential damage on buildings, their control implies assessing the material strains for the structural damages and limiting the drifts for the non-structural damages, also in the connections behaviour. Therefore, the studies presented in this paper, for the characterization of the cyclic behaviour of partial-strength joints through the connections modelling in a numerical simulation, are undertaken in such a way that the results can be directly applied in the direct displacement-based seismic design (DDBD) method proposed by Priestley et al. (2007). Contributing this way for the assessment of the necessary relationships in the moment resisting frame structures, with partial-strength joints, analysis and design by the DDBD approach, namely the equivalent viscous damping.

2. LITERATURE REVIEW AND METHODOLOGY

The partial-strength joints in seismic resistant steel structures have gained importance after the brittle damage found in steel welded joints after the Northridge (1994) and Kobe (1995) earthquakes. Research carried out after the two earthquakes by Calado (2003) showed the improved behaviour of frames with partial-strength joints due to the period elongation and damping increase resulting from the ductility and friction features of the connections.

Even though the monotonically loaded behaviour of partial-strength and/or semi-rigid joints can be defined and characterized accurately with the component method (CEN, 2005), when inelastic reversal load occurs the behaviour characterization and joint design are not addressed and experimental validation is required (CEN, 2005). Therefore, if joints are to be designed in order to contribute to the dissipative behaviour of moment resisting frames, research must be undertaken to characterize the moment-rotation relationships for typical hysteretic characteristics and ductility.

A considerable amount of experimental work has already been undertaken to characterize the cyclic behaviour of the connections in several fields of application. Bernuzzi et al. (1996) analysed the influence of the load history and geometrical mechanical parameters on the cyclic performance of the connections; Plumier & Schleich (1993) studied the contribution of the column shear panel to the energy dissipation, strength and rotation capacity of the joints. Adey et al. (1998) studied the effect of the beam size, bolt layout, end-plate thickness and extension stiffeners. Yorgun & Bayramoglu (2001) analysed the effect of the gap between the end plate and the column flange on the joint performance. The studies undertaken by Dubina et al. (2001, 2002) analysed the influence of symmetrical and antisymmetrical cyclic loading, concluding that the loading type influence occurs mainly through the contribution of the panel zone. The work developed by Guo et al. (2006) on the cyclic behaviour of stiffness and strength of stiffened and unstiffened extended end-plate connections of beam–column joints allowed concluding that the stiffeners have a remarkable influence in the higher load carrying and energy dissipation. In the field of the dynamic behaviour of frames with semi-rigid / partial-strength joints one can highlight the work by Elnashai and Elghazouli (1994) and Shen and Astaneh-Asl (1999) concluding that the earthquake frame behaviour exhibited ductile and stable response, confirming the improved behaviour of semi-rigid frames in seismic regions. Some models have already been proposed for the connections behaviour prediction. Examples are the mechanical model proposed by Calado (2003) to simulate the cyclic behaviour of top and seat with web angles bolted semi-rigid connections and damage accumulation, and the analytical models proposed by Kukreti and Abolmaali (1999) to predict the moment-rotation hysteresis behaviour, including the initial stiffness, ultimate moment capacity, ultimate rotation of the top and seat angles connections. In the field of the low-cyclic fatigue assessment Calado and Castiglioni (1996) studied a cumulative damage model and a general failure criterion. Bursi et al. (2002) studied the fracture behaviour of isolated T-stub connections with partial fillet welds. For the connections characterization in a cyclic components approach for the characterization of the joints behaviour, failure modes and ductility, Bursi et al. (2002) worked on the cracks characterization for the low-cyclic fatigue assessment of T-Stubs. Also it is important to point out the work developed by Faella et al. (2000) regarding the calibration of mathematical models for T-Stubs based on cyclic tests. Later, in the same field, the work of Piluso and Rizzano (2008) proposed an analytical model for the cyclic behaviour characterization calibrated by the T-Stub experimental tests. It should be also mentioned the proposed approach by Simões da Silva et al. (2009) for an extension to the component method for the end-plate joints cyclic behaviour. The most recent work on this field was done by Latour et al. (2011) considering that the connections overall energy dissipation can be obtained by the sum of the energies dissipated by the isolated components contribution. The proposed model is based on the passive energy dissipating system philosophy, namely the metallic dampers that take advantage of the hysteretic behaviour of metals in the inelastic range of deformation to dissipate the energy.

Although many studies were developed in the past years in the field of joints characterization when subjected to cyclic loading in the inelastic range, it still remains a gap in knowledge and it is notorious the absence of a consensus around a procedure capable of characterizing the cyclic behaviour of partial-strength or semi-rigid joints without resorting experimental tests.

The approach followed in the present research makes use of some of the reviewed experimental tests to calibrate numerical models that simulate the connections behaviour. The objective is to establish semi-analytic relationships for typical hysteretic characteristics and ductility. This allows the immediate determination of simplified expressions for important design values such as the equivalent viscous damping (EVD), needed for the direct displacement-based design (DDBD) procedure. The DDBD procedure utilises the concept of equivalent viscous damping to account for the energy dissipated during the dynamic response. The damping is considered as the sum of the elastic and hysteretic damping components:

$$\xi_{eq} = \xi_{el} + \xi_{hyst} \tag{1.1}$$

where the hysteretic damping, ξ_{hyst}, depends on the hysteresis characteristics of the structure. The elastic damping, ξ_{el}, for a SDOF system, is a relationship between the mass, the circular frequency and a fraction of the critical damping, ξ, and is used in the dynamic equation of equilibrium.

Beyond this, it is also aimed to parameterize the FE models in order to contribute to define the cyclic behaviour of joint components, in line with the requirements of the component method proposed for monotonic loading in Eurocode 3. The several phenomena involved in the connections behaviour, mainly in the bolted ones, make the prediction of the cyclic behaviour a complex task, as realised by Nogueiro et al. (2007). The high number of elements involved in the connection zone, the material reversal non-linearity in the plastic range with strain-hardening, the geometrical non-linearity, the non-linear contact and slip, the residual stress conditions among other phenomena bring additional difficulties to the modelling of the connection behaviour. Because of that, experimental tests are a good mechanism to obtain this characterization however particularly expensive and limited in number. The significant development in the computer technology provides the opportunity to extend the application of the numerical models to perform parametric studies, as realised by Ádány and Dunai (2004), calibrated by the experimental tests available. The finite element method is a powerful tool to model the cyclic behaviour of joints.

In this work isolated T-Stub components models and complete connections models have been developed. The results are compared with experimental test data. A procedure to determine the equivalent viscous damping is described which is based on non-linear time history analysis(NLTH) performed on single degree of freedom (SDOF) systems incorporating the modified Richard-Abbott mathematical model (Della Corte et al., 2000) which can simulate the cyclic path of a curve through the calibration of a set of parameters. Values of equivalent viscous damping are obtained for increasing levels of rotation ductility demand and for several elastic periods of vibration.

3. DESCRIPTION OF THE SPECIMENS USED IN THE MODEL CALIBRATION

The use of experimental cyclic tests to calibrate the numerical models is a crucial step since the real cyclic behaviour of a given joint may differ substantially from an idealised behaviour. Therefore, for each type of connection a series of experimental tests were chosen to calibrate the numerical models. The T-stub models were developed on the basis of the experimental tests of Piluso and Rizzano (2008) and on the results of the coupons materials tests kindly provided by the same authors. The beam-to-column extended end-plate connection model was defined on the basis of the J1 series specimens tested by Nogueiro et al. (2006).

3.1. Tests on T-stub Specimens

The geometrical properties of the laminated profiles used in the tests, half HEA180 and HEB180, are listed in Table 3.1, and can be seen in Fig. 3.1. The bolts were M20 grade 8.8 in all cases.

Table 3.1. Measured geometrical properties of tested specimens

Series	Test	B (mm)	b (mm)	t_f (mm)	t_w (mm)	r (a) (mm)	m (mm)	n (mm)
A: HEA 180	A2	181.75	158.25	9.68	6.83	15.00	37.23	38.24
B: HEB 180	B7	180.00	158.25	14.19	8.15	15.00	36.71	37.21

The stress-strain data for the HEA 180 and HEB 180 is provided in Table 3.2. For the bolts, the nominal values for the 8.8 class were used.

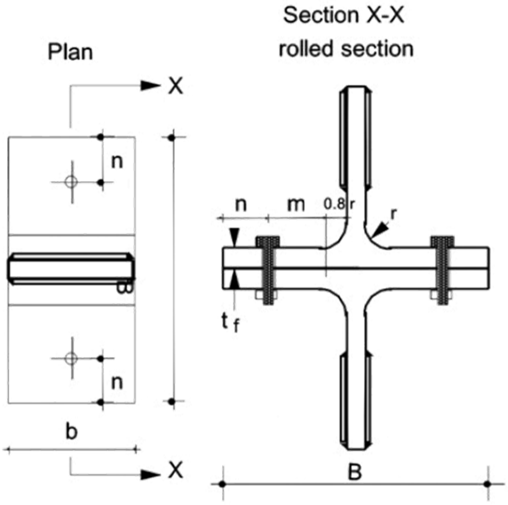


Figure 3.1. Geometry of bolted T-Stubs (figures from Piluso and Rizzano, 2008)

Table 3.2. Measured geometrical properties of tested specimens

Series	A_0 (mm^2)	ε_u (%)	f_y (N/mm^2)	f_u (N/mm^2)
A: HEA 180	207.82	98.28	334.67	530.62
B: HEN 180	106.28	109.92	280.10	464.56

where ε_u is the ultimate natural strain ($\varepsilon_u = ln\ A_0/A_f$ being A_0 the original cross-sectional area of the specimen and A_f the minimum cross-sectional area after fracture) and f_y and f_u are the yielding and ultimate strength, respectively.

3.2. Tests on an End-Plate Connection Specimen

The test specimen consists of an external extended end-plate connection between a HEA320 column profile and an IPE360 beam profile. The end-plate has a thickness of 18mm and 8 bolts M24 grade 10.9, four around each beam flange (Fig. 3.2). The bolts were pre-tensioned with an equivalent force of approximately 20% of the ultimate tensile strength of the bolt. In the column two stiffeners were provided in the alignment of the beam flanges with 15mm thickness. The steel grade of the profiles and plates was S355.

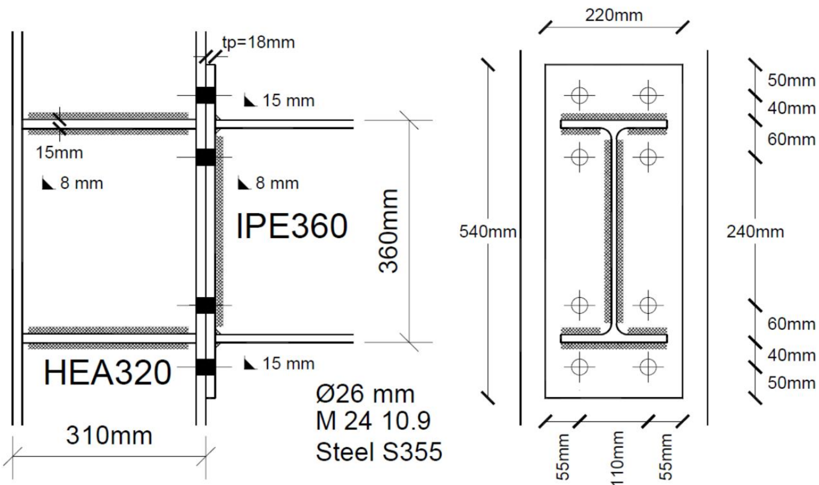


Figure 3.2. Connection detail (figures from Nogueiro et al., 2006)

The mean results from the coupons tension tests are summarized in Table 3.3.

Table 3.3. Mean values for the stress-strain relationships

Components		Yield stress (MPa)	Elastic Modulus (GPa)	Ultimate stress (MPa)	Ultimate strain (%)	Strain at rupture (%)
		f_{ym}	E_m	f_{um}	ε_{um}	ε_{rm}
Flanges	IPE360	430.0	206.0	554.2	15	25
	HEA320	414.8	204.9	531.4	17	29
Webs	IPE360	448.2	213.6	552.9	16	26
	HEA320	449.6	207.4	553.4	15	24
End-plate		392.9	208.4	523.0	14	24
Stiffeners		286.4	205.9	451.8	20	30
Bolts		990.0	213.0	1170.0	11	34

4. FINITE ELEMENTS MODELS

4.1. T-Stub Models

Solid three-dimensional models with contact elements and that incorporate non-linear constitutive laws for materials were developed in ABAQUS 6.11 (2011). The most used element in the models was the solid (or continuum) quadrilateral and hexahedra, designated by C3D8RH, which is an 8-node linear brick element, with hybrid formulation, constant pressure, reduced integration and hourglass control. For the regions where the hexahedra formulation was not possible to be used the wedge approach was used with an element designated by C3D6H which is a 6-node linear triangular prism, hybrid and constant pressure element. Whenever possible, the meshes adopted were composed by hexahedral elements because usually they provide a solution of equivalent accuracy (comparing to the tetrahedral ones) at less computational cost. Reduced integration elements were chosen using a lower-order integration to form the element stiffness. This option saves considerably running time but in contrast can result in hourglassing issues, because of having only one integration point in its formulation. To control the problem, a first-order with reduced-integration element available in ABAQUS which incorporates hourglass control and a thickness refinement were used. The choice of reduced integration elements allows overcoming the shear locking phenomena.

The general contact algorithm was used to take into account the contact between the T flanges and between the bolt surfaces, nut, head and body with the T sections holes and flanges surfaces. The simulation of the material hardening when subjected to cyclic loads was represented with the combined isotropic/kinematic model available in ABAQUS. This constitutive model is based on the work of Chaboche (1986) and uses the Von Mises (1913) yield criterion assuming an associative flow rule.

As for the loading histories applied to the models, the A2 series were subjected to 57 cycles with constant amplitude of 10mm and the B7 series were subjected to 13 cycles with constant amplitude of 20mm.

4.1. End-Plate Connection Models

With the objective of saving computational time, an hybrid finite element models was used to simulate the end-plate connections. 3D solid elements were used to represent the connection region while beam fibre elements were used in the adjacent regions (beam and column). The choice of the element type took into account the same criteria used for the T-stub models. The FE meshes developed in ABAQUS are shown in Fig. 4.1.

The column (HEA320), beam (IPE360), bolts and extended end-plate were modelled using solid (or continuum) quadrilaterals and hexahedra, designated by C3D8RH in ABAQUS. To optimize the computational time, the beam (IPE360 profile) was modelled with C3D6 elements without the hybrid formulation. For the adjacent regions, 2-node linear beam elements were used designated by B31 in ABAQUS.

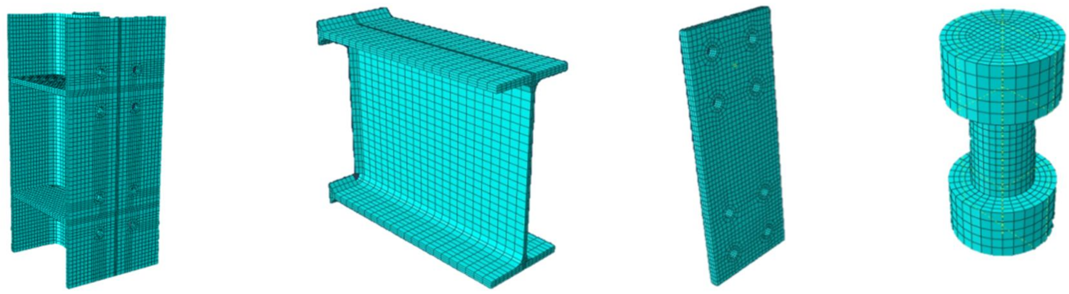


Figure 4.1. Connection parts mesh, from left to right, column, beam, end-plate and bolts

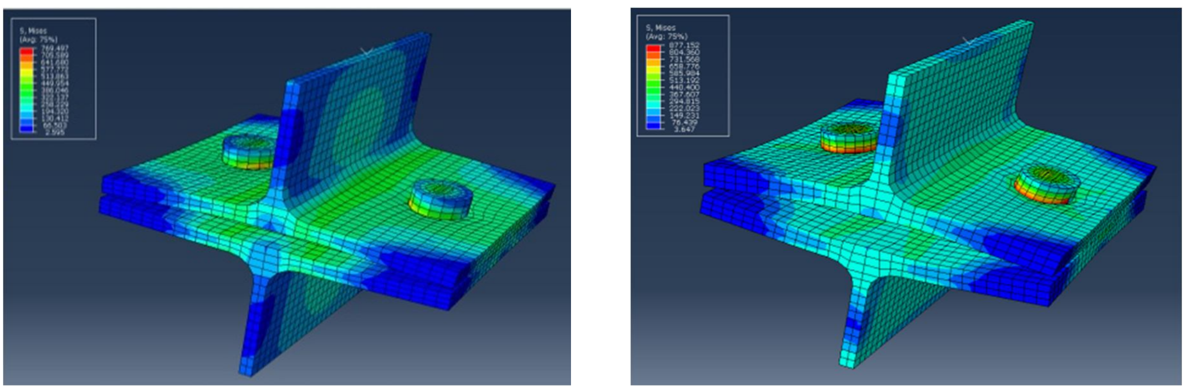
The link between the solid elements and the beam elements was established with the coupling constraint feature available in the program. The hard contact formulation was used to take into account the contact between the end-plate, column flange and the bolts surfaces. Regarding the material characterization in the cyclic inelastic field the combined hardening model available in ABAQUS was used, similar to what was adopted for the T-stub models.

The application of the cyclic load was performed according to the ECCS (1986) recommendations, by controlling the displacement at the tip of the beam. Cycles of increasing amplitude were applied: (i) $(\theta_y \times 6)/4$; (ii) $2(\theta_y \times 6)/4$; (iii) $3(\theta_y \times 6)/4$, where θ_y denotes the yield rotation of the connection. This was followed by a constant cyclic displacement corresponding to $\theta_y \times 6$ mrad until the connection reached the cycle corresponding to failure observed in the experimental test.

5. RESULTS AND DISCUSSION

5.1. T-Stub Models

As shwon in Fig. 5.1 (a) and Fig. 5.2 (a), for the cyclic response the numerical results had good agreement with the experimental ones mainly in the A2 tests, representing the type-1 collapse mechanism, i.e. flange yielding, according to Eurocode 3. For the B7 tests, although with less agreement the results were still acceptable representing the type-2 collapse mechanism, i.e. flange yielding with bolt fracture (EC3). The comparison of the results is shown in Fig. 5.1 (b) and Fig. 5.2 (b).



(a) (b)

Figure 5.1. Von Mises stress distributions: (a) A2 (amplitude of 10mm) (b) B7 (amplitude of 20mm)

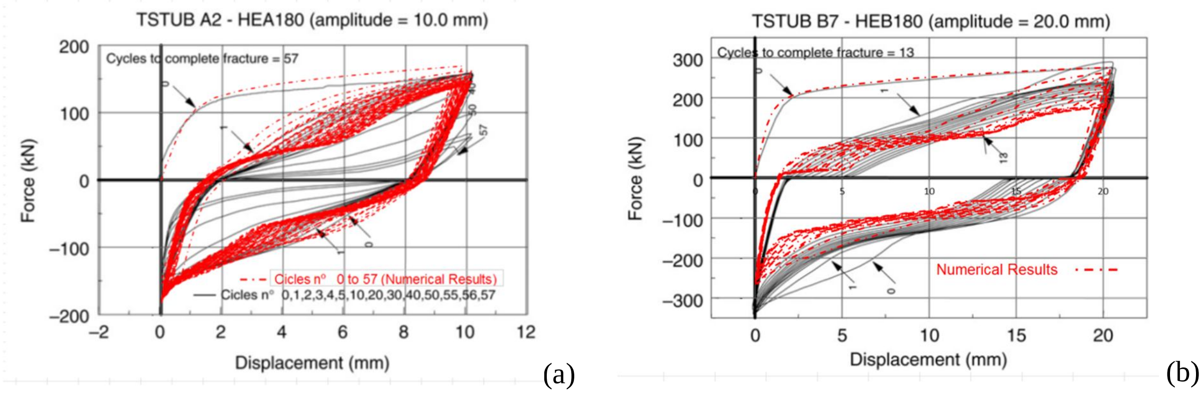


Figure 5.2. Comparison between the numerical and experimental results: (a) A2 specimen; (b) B7 specimen

5.2. End-Plate Connection Models

Fig. 5.3 depicts the results obtained for the web rotation along with the experimental response. The initial cycles are quite well adjusted with the test results but there is a small mismatch in terms of maximum moment. With small adjustments in the yield stress of the web material (about 15% less) the numerical results show better agreement with the test (Fig. 5.3 (b)). However, it was considered that the accuracy of the first results is sufficient and therefore it was decided not to introduce any changes in the material properties obtained in the coupon tests.

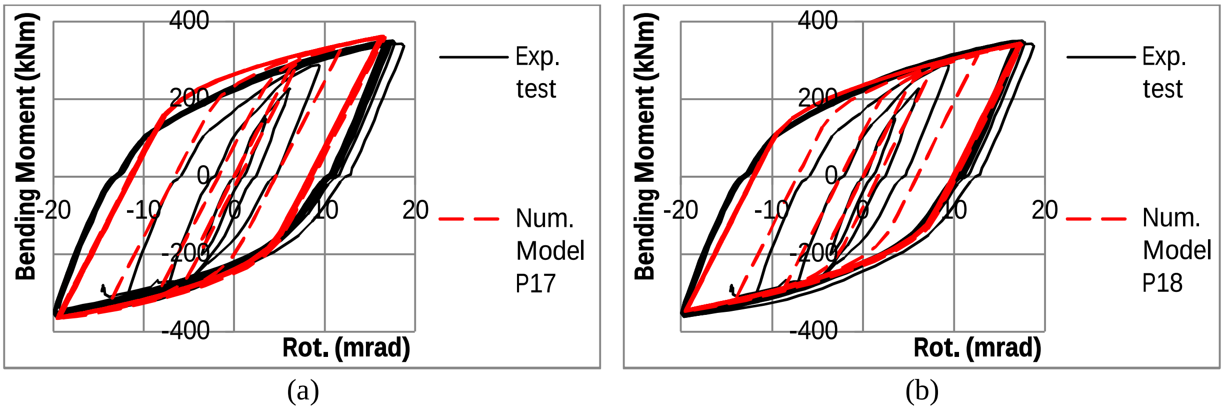


Figure 5.3. Comparison between the numerical and experimental results

The Equivalent Plastic Strain (PEEQ) provided by the ABAQUS model is shown in Fig. 5.4 (a) (deformation amplified 5 times). Fig. 5.4 (b) illustrates the deformation observed during the tests.

The results of this model were satisfactory and are the base for the subsequent models to be prepared in the parametric study in the on-going work.

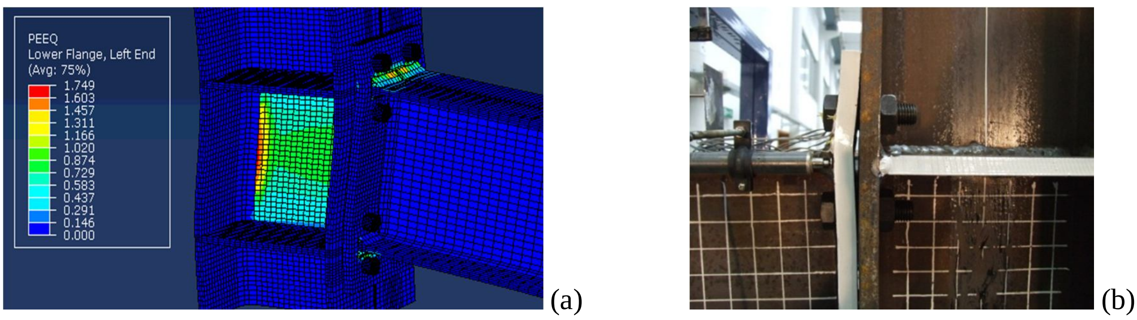


Figure 5.4. (a) J1.3 results - PEEQ representation; (b) J1.3 Experimental test end-plate deformation

6. EQUIVALENT VISCOUS DAMPING EVALUATION

6.1. Description of the Procedure

The procedure adopted in the assessment of the EVD comprises the following steps:

1) Based on a SDOF system with a cyclic behaviour defined according to the Richard-Abbott model, and for a specified effective period, T_e, obtained with Eqn. 6.1, a ductility, μ, is imposed, Eqn. 6.2. As shown in Fig. 6.1, it is therefore possible to calculate the target displacement (Δ_d) (or target rotation, θ_d) and corresponding force (or moment).

$$T_e = \frac{2\pi}{\sqrt{\frac{k_e}{m}(1-\xi^2)}} \tag{6.1}$$

$$\mu = \frac{\Delta_d}{\Delta_y} \tag{6.2}$$

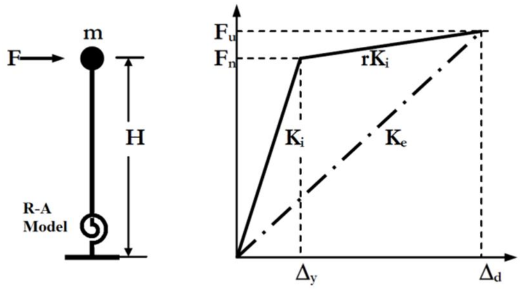


Figure 6.1. SDOF system representation

2) A NLTH analysis is performed using a pre-selected seismic record and tangent-stiffness proportional damping of 3%. The maximum displacement/rotation (Δ_{max} /θ_{max}) is recorded. If $\theta_{max} \neq \theta_d$ ($\Delta_{max} \neq \Delta_d$) then the record is scaled and the analysis is repeated, until the $\theta_{max} = \theta_d$ (or $\Delta_{max} = \Delta_d$) condition is reached.

3) Using the software SeismoSignal V4.3.0 (SeismoSoft, 2011a), the displacement spectra of the scaled record are determined for various levels of viscous damping, ξ_{eq}.

4) Since the effective period, T_e, and the design displacement Δ_d (or rotation θ_d) are known, the equivalent viscous damping can be determined from the displacement spectra.

6.2. Preliminary Results

The NLTH analysis were carried on SeismoStruct V5.2.2 (SeismoSoft, 2011b) that incorporates the modified Richard-Abbott mathematical model (Della Corte et al., 2000) implemented by Nogueiro et al. (2005), which can simulate the cyclic path of a curve through the calibration of a set of parameters. The parameters for the J1 series connections are those presented in the work of Nogueiro et al. (2006).

The values of EVD obtained are plotted in Fig. 6.2. These results should be taken as preliminary due to the reduced number of analyses performed, and also because the results were obtained for a single seismic record. It is expected that more conclusive results will be obtained in the course of the research, including considerations due to the type of beam-to-column connection. In Fig. 6.2 the results obtained from the proposed expression (Eqn. 6.3) by Priestley et al. (2007) for steel frame buildings with a Ramberg-Osgood hysteresis rule are also represented considering a ductility demand between 1.5 and 5.

$$\xi = 0.05 + 0.577\left(\frac{\mu-1}{\mu\pi}\right) \tag{6.3}$$

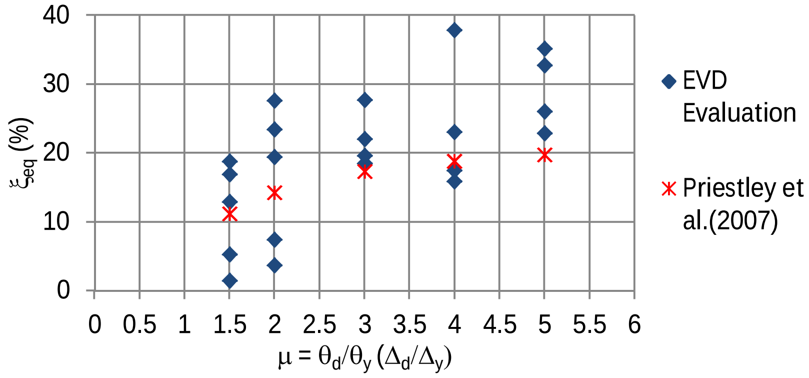


Figure 6.2. EVD evaluation results

7. CONCLUSIONS

In order to develop reliable beam-to-column connection models and to capture the behaviour of the isolated connections components, FE models of T-Stubs models were developed and the results were compared with experimental test data. For these models, it was concluded that the accuracy obtained with the ABAQUS combined isotropic/kinematic model (based on the work of Chaboche, 1986) are adequate with reasonable computational effort. Complete connection models were also produced, choosing a connection tested by Nogueiro et al. (2006). The quality of the results obtained in the calibration of the numerical models using the experimental tests data allows foreseeing and preparing for new simulations of the partial-strength connections cyclic behaviour.

The modified Richard-Abbott model (Della Corte et al., 2000) implemented in the software SeismoStruct V5.2.2 (SeismoSoft, 2011b) was used to undertake non-linear time history analyses of single degree of freedom system, with previously selected records. The scaling of the record and of the displacement spectrum was used to evaluate the equivalent viscous damping needed for the application in the direct displacement-based design method. It was observed that the procedure for the EVD evaluation is very sensitive to the effective period and target displacement. The preliminary results are promising and will be expanded by increasing the number of analyses and seismic records. In the next stages of the research a parametric study will be undertaken with the objective of building a connections database covering the partial-strength steel connections used in practice.

AKCNOWLEDGEMENT

The authors gratefully acknowledge that the research leading to these results has received funding from the European Union's Research Fund for Coal and Steel (RFCS) research programme under grant agreement n° [RFSR-CT-2010-00029].

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