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Innovative Dissipative (INERD) Pin Connections for Seismic Resistant Braced Frames

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Abstract

Innovative dissipative (INERD) connections were developed for seismic resistant braced frames. The dissipative zones in such frames are the connections, while the braces are protected against buckling. Two types of INERD connections were developed: pin connections and U-shape connections. This paper presents studies on the pin connections, where the braces are connected to their adjacent members by means of eye-bars and a pin running through them. Experimental and theoretical investigations show a high energy dissipation capacity of these connections that is due to the inelastic bending action of the pin. The susceptibility to brittle fracture or low-cycle fatigue is low as inelastic action takes place away from welds or stress concentrations. Design rules for the connections are developed. The beneficial mechanical behaviour and other constructional advantages provide a promise for a wide application of the invented connections for buildings and engineering structures in seismic regions.

Key words: Connections, Dissipative, Steel, Braced Frames, Earthquakes

1. Introduction

Earthquake resistant steel frames are usually designed so that they exhibit a dissipative structural behaviour. In such a case, parts of the structure (dissipative zones) exhibit inelastic deformations during strong seismic motions. The main structural typologies (Mazzolani *et al.*, 2000), the correspondent performance characteristics and the expected positions of the dissipative zones are listed in Table 1. It may be seen that conventional frames (columns 2 to 4) have certain disadvantages in respect to stiffness or ductility. Additionally in such frames, following problems arise after strong earthquakes due to the position of the dissipative zones, where damage is expected to concentrate: a) the need for strengthening or replacement of damaged and buckled braces which have a certain length and are difficult to handle, b) the need for strengthening and repair of the links or the beams that are part of the main system that supports gravity loading. Such works require considerable skill and are associated with high material and labour costs.

Damages in steel framed structures after recent strong earthquakes indicate the need for improvement of existing structural typologies and for introduction of innovative systems. These systems shall have the following properties: a) High stiffness in order to limit drifts during moderate seismic motions, b) high ductility in order to dissipate energy during strong motions and c) possibility for easy inexpensive repair, if required. In the present paper, a new system with such properties, applicable mainly to concentric, but possibly also to eccentric braced frames is presented (Table 1, column 5).

The system was developed and studied during a joint European research project, involving 4 Universities (Athens, Lisbon, Milan and Liege) and a steel production Company (Arcelor/Arbed). Supplementary investigations were performed during a national Greek research project, involving the National Technical University of Athens and 5 Software and Construction companies. A priority European Patent Application has been filed on the invented connections.

Braced frames with INERD-connections exhibit the following benefits compared to conventional steel frames:

- Better compliance with the seismic design criteria (Table 1, column 5).
- Protection of compression braces against buckling.
- Activation of all braces, either in compression or in tension, even at large storey drifts.
- Limitation of inelastic action and damage in small parts of the structure that may be easily replaced.
- Avoidance of brittle fracture and/or low-cycle fatigue.
- Possibility for easy inexpensive repair after very strong earthquakes, if required.
- Reduction of overall structural costs for the same performance level.

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Table 1. Structural typologies and main characteristics for Steel Frames

1	2	3	4	5
	Moment resisting frames (MRF)	Concentric braced frames (CBF)	Eccentric braced frames (EBF)	CBF or EBF with INERD connections
Stiffness	Low	High	Moderate	High
Ductility	High	Low	Moderate	High
Dissipative zones at	Beams	Braces	Link beams	Connections

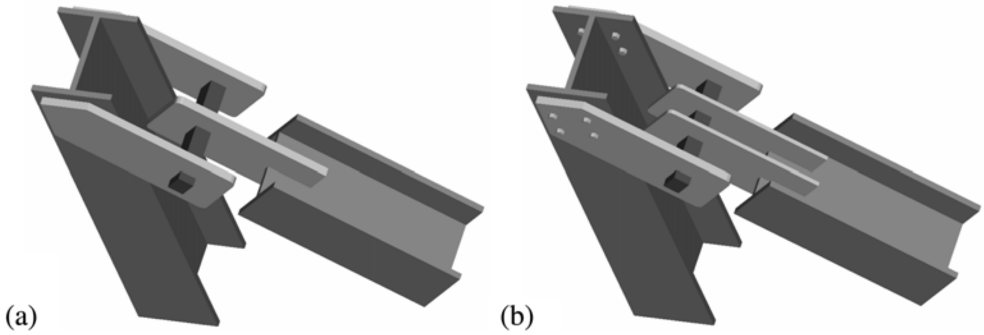


Figure 1. Rectangular pin connection with one or two internal eye-bars.

2. Description of the INERD Connections

According to the current European seismic rules (Eurocode 8, 2004), "concentric braced frames shall be designed so that yielding of the diagonals in tension will take place before failure of the connections and before yielding or buckling of the beams or columns" and that "in frames with diagonal bracings, only the tension diagonals shall be taken into account". The former condition leads to high connection costs for conventional braced frames, since the connections shall be stronger than the connected members and remain elastic during the seismic excitation. The latter indicates that the compression braces, almost half of the total, are considered, due to buckling, as inactive, which evidently leads to heavier brace sections and higher costs.

However, Eurocode 8 leaves the door open for the development of innovative dissipative connections, as it states that "The overstrength condition for connections need not apply if the connections are designed to contribute significantly to the energy dissipation capability inherent to the chosen q-factor and if the effects of such connections on the behaviour of the structure are assessed". The hereafter presented INERD connections fall into the above category and are therefore weaker than the connected members, exhibiting inelastic deformations and dissipating energy during seismic loading. Two types of INERD connections connecting the braces to the adjacent members were developed: a) pin connections and b) U-connections.

The pin connections consist of two external eye-bars welded or bolted to the adjacent member (column for X-braces, beam for V or eccentric braces), one or two internal eye-bars welded or bolted to the brace and a pin running through the eye-bars, as indicatively shown in Fig. 1. Inelastic deformations and energy dissipation concentrate in the pins. The pin cross section is not round in order to avoid twist around its axis during cyclic loading. Accordingly, two pin cross sections were selected: a) either rectangular, where the pin is bent around its small side (in order to avoid possible lateral buckling), or b) rectangular with rounded edges, where the pin is bent around its large side.

The U-connections consist of U-shaped thick plates that connect the brace to the adjacent member, with one leg parallel or perpendicular to the brace axis, as shown in Fig. 2 where the brace load is applied horizontally. Here again, energy dissipation takes place in the bent plates. The advantage of these connections is that, by appropriate sizing, inelastic deformations are limited within exactly predetermined zones, the pins or the U-plates, whereas the adjacent parts remain elastic. Consequently, damage takes place away from welds or notches and is restricted to the pins or the U-plates that may be easily replaced, if largely deformed, after a strong earthquake.

The study of the performance of the new system included experimental and theoretical investigations, as following:

- Full-scale tests on INERD connection details performed in Lisbon (Calado and Ferreira, 2004).
- Full-scale tests on frames with INERD connections performed in Milan (Castiglioni *et al.*, 2004).
- Analysis of INERD pin connections performed in Athens (Vayas *et al.*, 2004).
- Analysis of X-braced frames with INERD pin connections (Vayas *et al.*, 2004).

Figure 2. U-connection with one leg parallel or perpendicular to the brace axis (load horizontally applied).

The present paper is focused on the analyses of the pin connections. For details of the experimental investigations reference is made to the relevant research reports indicated above.

3. FEM Analyses for Cyclic Loading

The behaviour of the pin INERD connections has been studied by FEM analyses that provide useful information for the monotonic and cyclic response of the connections at large inelastic deformations. The analyses were made using the general purpose programme ABAQUS, version 6.4. The contact between the eye-bars and the pin, was modelled by applying special interaction properties between the appropriate surfaces, as ABAQUS provides a vast variety of contact properties (e.g. stiffness, friction etc.) to select from. Making use of the double symmetry properties allowed for modelling of one quarter of the connection that included one half of an external and one half of an internal eye-bar and a quarter of the pin. Monotonic loads were applied in the analysis through axial displacement control up to 50 mm. Cyclic loading was applied in cycles, the amplitude of which increased by 5 mm from that of the previous ones. The analyses were made in a first step for the connections that were tested experimentally by Calado and Ferreira in Lisbon, in order to allow a validation of the relevant models. Accordingly four configurations with two internal eye-bars were analyzed, together with two extra ones with one internal eye-bar that were investigated only analytically (Table 2). It may be mentioned that the cyclic tests were performed according to the ECCS testing procedure with three equal full cycles at the prescribed displacements, ECCS 1986, while in the analysis one full cycle was applied.

Figure 3 shows the connection at large displacements, together with the von Mises stresses, indicating:

a) the spread of plasticity in the pin around the internal eye-bars

b) the plastic deformations at the inner side of the external eye-bars

c) the hole ovalisation in the eye-bars and

d) the transverse deformations, especially of the thinner eye-bars.

Figure 4 shows the response of the connection type D as determined by the tests and the FEM analysis. The material stress vs. strain law was taken such that allowed for the inclusion of Bauschinger effects which appeared to be important. The friction coefficient between the pin and the eye-bars was taken equal to 0.4. It may be seen that the connection strength to positive loading (eye-bars in compression) is higher than the relevant strength to negative loading (eye-bars in tension) for reasons to be explained later. Some pinching is observed due to ovalisation of the holes of the eye-bars, otherwise stable hysteretic loops are achieved. Similar satisfactory agreement between experimental and FEM results was observed for all types of tested connections. It may be stated that the analyses and the tests indicated that the monotonic curves represent skeleton curves of the cyclic ones, except at low deformations where they are stiffer than the latter.

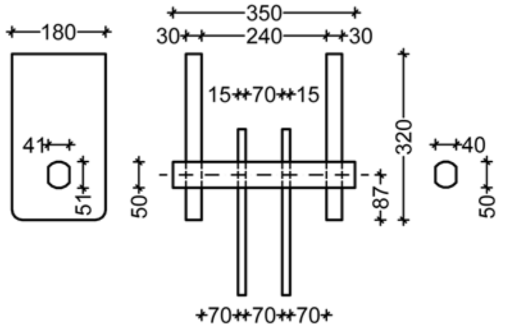
Figure 5 shows FEM results of the same connection without consideration of Bauschinger effects (bilinear material law). It may be seen that this analysis does not correctly express the connection response in that it predicts initiation of slipping at almost constant forces.

As previously mentioned, the eye-bars tend to exhibit transverse inelastic deformations during cyclic loading. Figure 6 shows analysis results for these deformations for the connection type D and a picture of the connection after the test, where these deformations are visible. It may be seen that: a) the external eye-bars deform outwards, while the internal inwards, b) these deformations are accumulating in the cycles, increasing thus both the overall span (distance between external eye-bars) and the internal span (distance between external and internal eye-bars) of the pin, c) the transverse deformations are higher for the, thinner, internal eye-bars than the, thicker, external ones. Obviously if only one internal eye-bar is used (Table 2, types E and F) the relevant transverse deformations disappear due to symmetry.

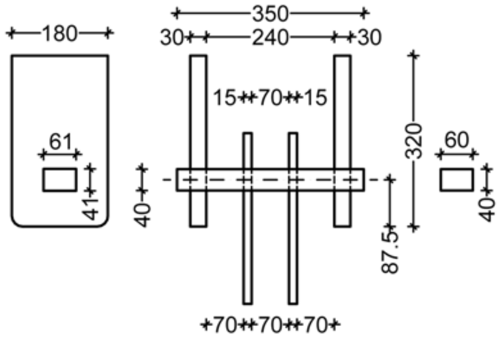
The applied moment on the pin, and therefore the connection strength, is linearly varying with the distance

Table 2. Configurations used for testing and FE analysis

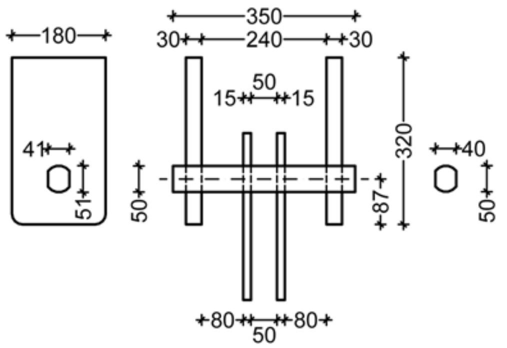
Type A (rounded section, distance 70 mm)



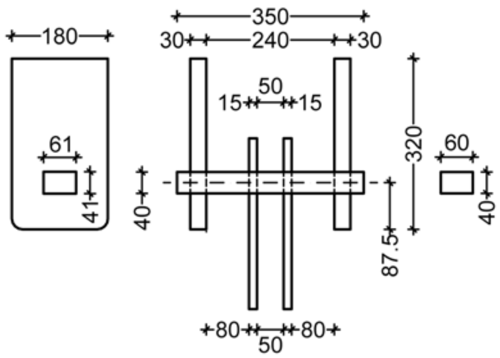
Type B (rectangular section, distance 70 mm)



Type C (rounded section, distance 50 mm)

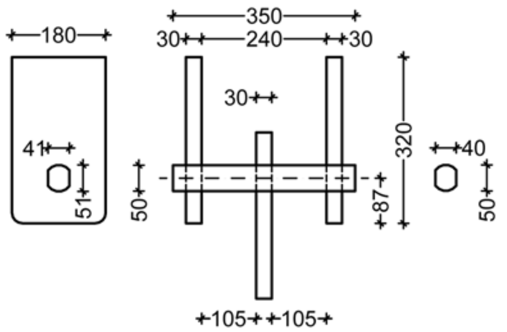


Type D (rectangular section, distance 50 mm)

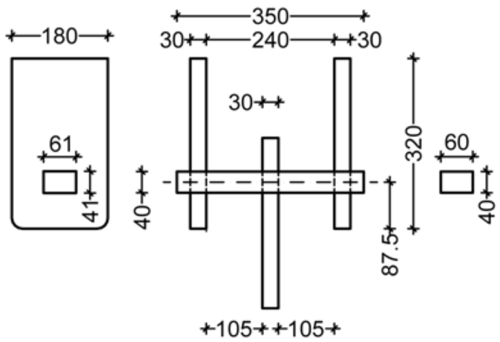


Thickness of external eye-bars 30 mm and internal eye-bars 15 mm (Tests and FE analysis)

Type E (rounded section, one internal eye-bar)



Type F (rectangular section, one internal eye-bar)



Thickness of external and internal eye-bars 30 mm (FE analysis only)

between external and internal eye-bars. This is confirmed by the FEM analyses (Fig. 7), that show the response of the connection types B and D (Table 2), as well as the connection type F with one internal eye-bar whose thickness is equal to the thickness of the external ones (= 30 mm).

The dissipated energy of the above connections is shown if Fig. 8. It may be seen that the connections are dissipating large amounts of energy even al large displacements. The dissipation capacity is higher for stronger connections (smaller distance between eye-bars). But connections with one internal eye-bar, type F, possess also a high dissipation capacity, comparable to those with two eye-bars. By varying the number and distance of eye-bars, the connections may be designed according to the strength and dissipation demand of the structure under consideration.

Subsequently, the dissipation capacity of braced frames with and without INERD connections was compared. For this purpose conventional X-braced frames in which energy dissipation takes place through inelastic action of the tension diagonal were studied. The inelastic brace response to cyclic loading was modelled by means of experimentally derived curves (Black *et al.*, 1980), as shown in Fig. 9. The overall response of the X-braced frame results obviously from the addition of the two

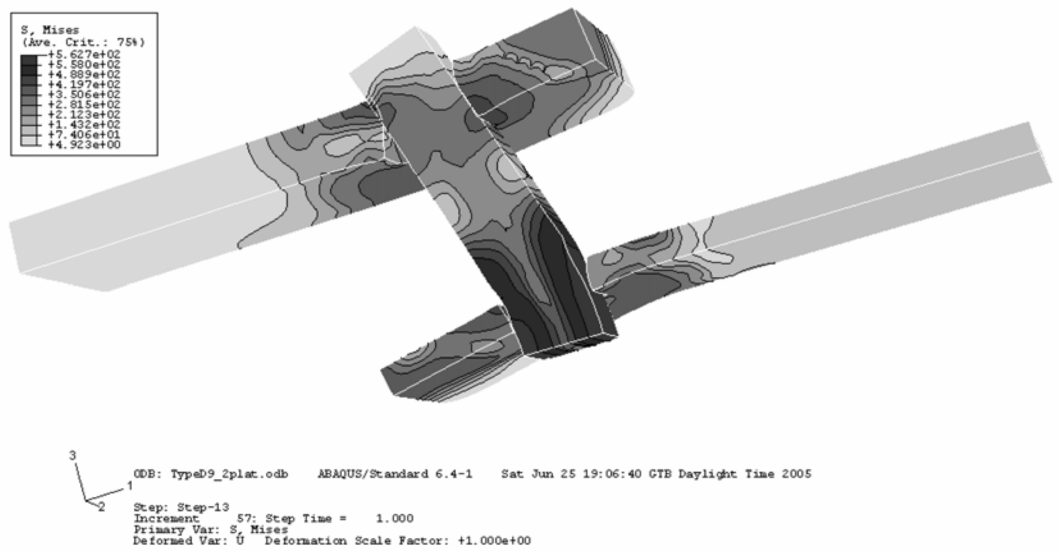


Figure 3. FE model for the pin connection in the deformed state at large displacements (1/4 of connection).

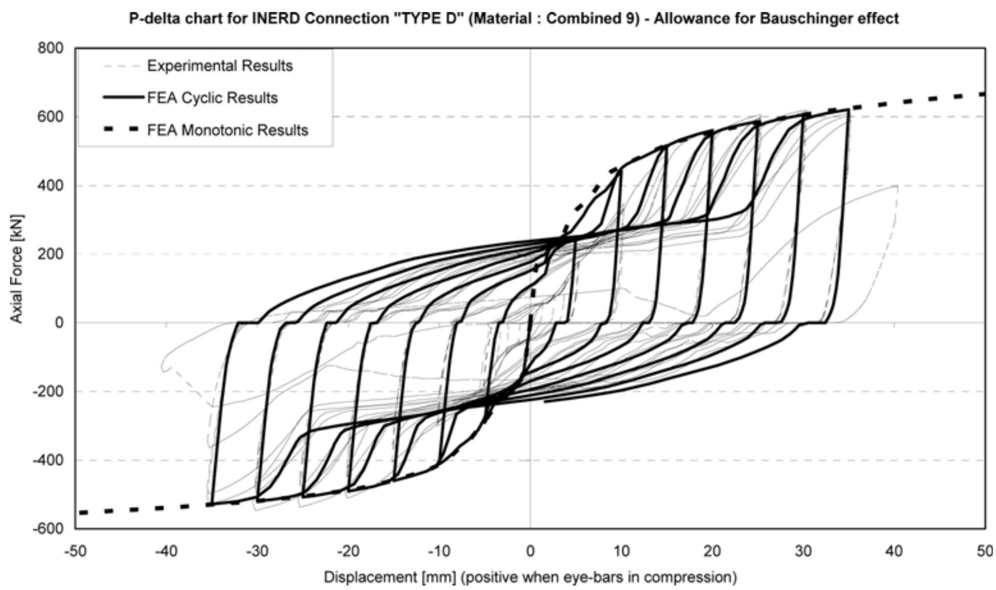


Figure 4. Experimental vs. FEM results of connection Type D.

brace responses, one in compression one in tension. In the frame with the INERD connections, all four connections are participating in the energy dissipation.

Three frame configurations were studied: a) a frame with dissipative INERD connections type B, b) a frame with non-dissipative connections with moderate brace slenderness and c) like b), but with larger brace slenderness. For comparison, the braces in cases b) and c) exhibited equal compression strength which was equal or slightly less than the connection strength of case a). Figure 10a shows the cumulative energy dissipation of the three cases. It may be seen that the dissipation capacity of the frame with INERD connections is much higher than for the conventional frames where the dissipative elements are the braces. The energy dissipation for the more slender brace ($\lambda = 1{,}08$) is higher than the correspondent one of the more compact brace ($\lambda = 0{,}85$). This is due to the fact that both braces have equal compression strength, so that the former has a larger section. However, if the energy is normalized by the tension capacity (Fig. 10b), as an expression of the structural weight, it is higher for the compact brace and lower for the slender one. It may be seen that the dissipation capacity for the frame with the INERD connection is even more pronounced in normalized terms compared with the conventional braced frame.

Some allowance of holes in the eye-bars is required for constructional reasons, in order for the pin to pass through them. Figure 11 shows analyses results for connection type B with 1 and 2 mm allowance. It may be seen that a smaller allowance for holes results in a better performance, especially at the initial loading cycles and

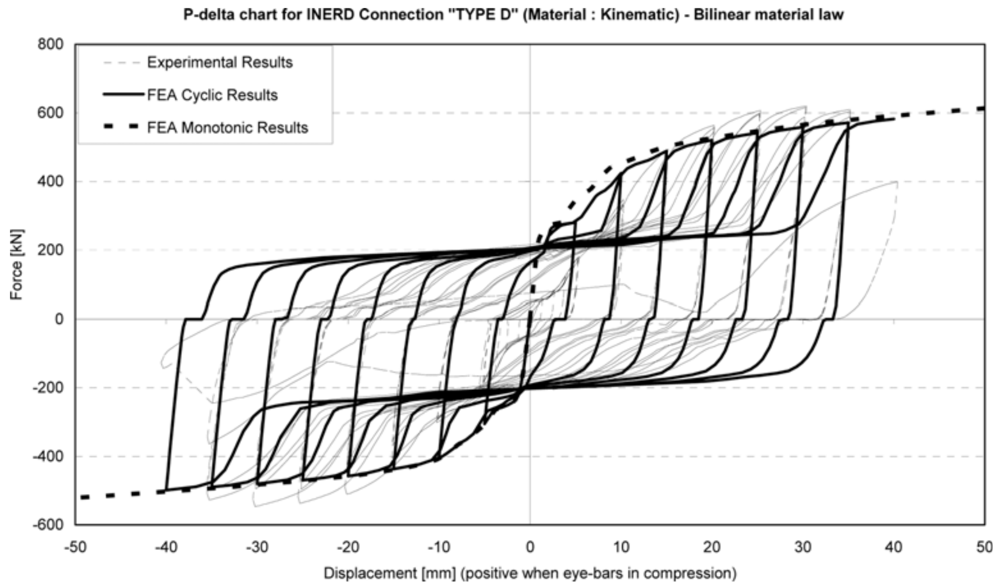


Figure 5. FEM results of connection in Fig. 4, without consideration of Bauschinger effects.

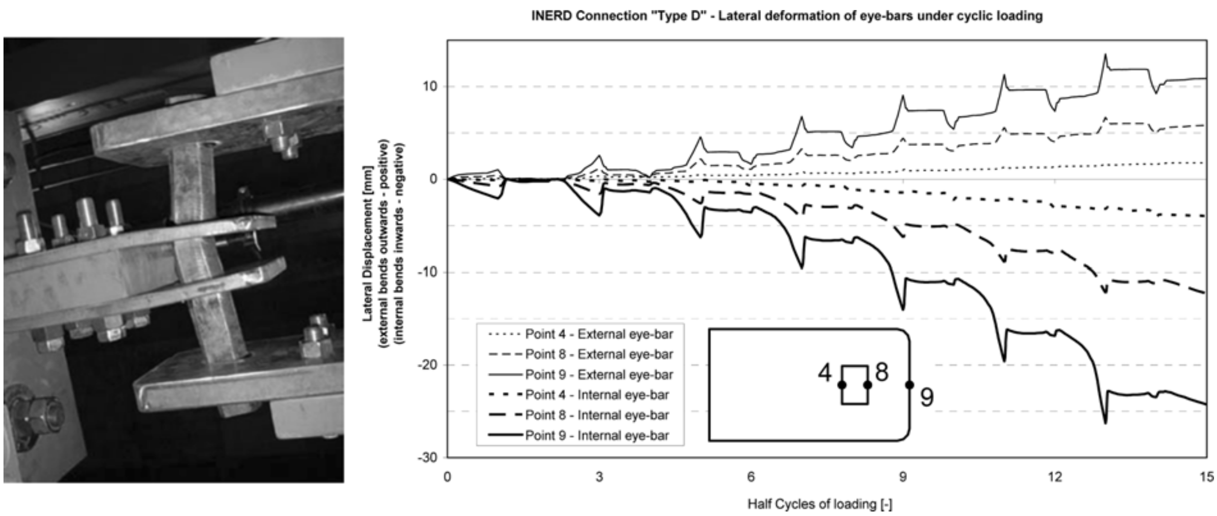


Figure 6. Lateral deformations of eye-bars.

in the compression side. However, at larger cycles the differences gradually disappear. Accordingly, a 2 mm maximal allowance for holes should be permitted for practical applications.

It may be added here that constant amplitude cyclic tests until fracture were carried out in Lisbon by Calado & Ferreira, 2004. Evidently, the number of cycles to fracture was a function of the level of applied deformations. The tests indicated a low susceptibility of INERD pin connections to fatigue and fracture. This is due to the fact that fracture takes place near the loading points, away from welds, notches or other discontinuities.

4. Design Rules for the INERD Connections

In order to develop design rules for the INERD connections, parametric FEM studies for monotonic loading, which provide skeleton curves, were preformed. Here the pin dimensions, the plate thicknesses, the material properties for the pins and the eye-bars and other properties were investigated. In this section results for connections with two internal eye-bars will be presented as the studies with one internal plate are still in progress. Figure 12 shows the response of one such group of connections in which the pin material has the same yield strength as the plates. Each curve corresponds to a different thickness of the external eye-bars, while the thickness of the internal plates remains constant and equal to 15 mm.

The connection response in the initial loading stages corresponds to that of a beam subjected to four-point bending. After the formation of two plastic hinges under the loading points, the beam becomes theoretically a mechanism. However, the external eye-bars provide a “clamping” effect to the pin which is higher for thicker external plates. The load can thus be further increased,

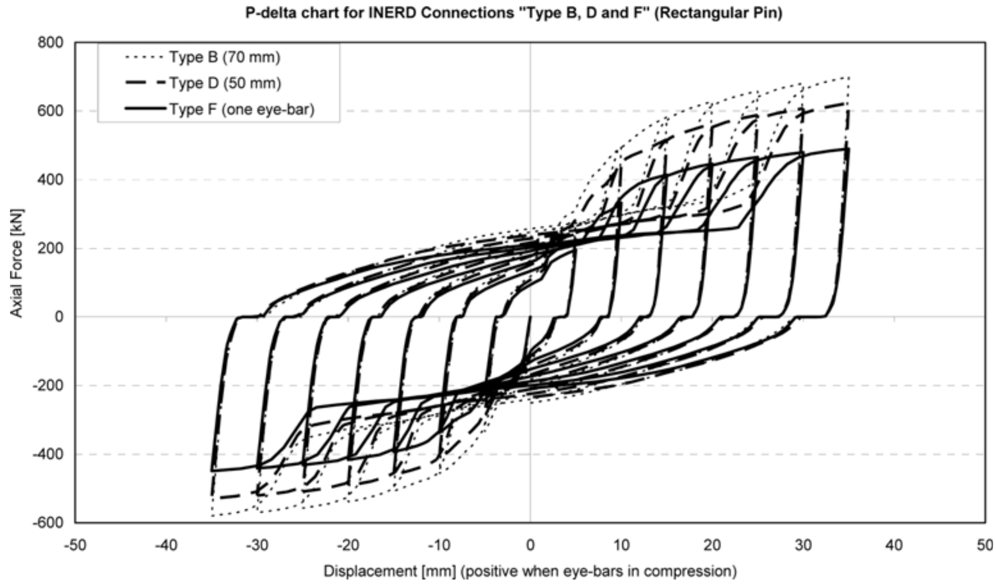


Figure 7. Response of connections B, D (two internal eye-bars) and F (one internal eye-bar).

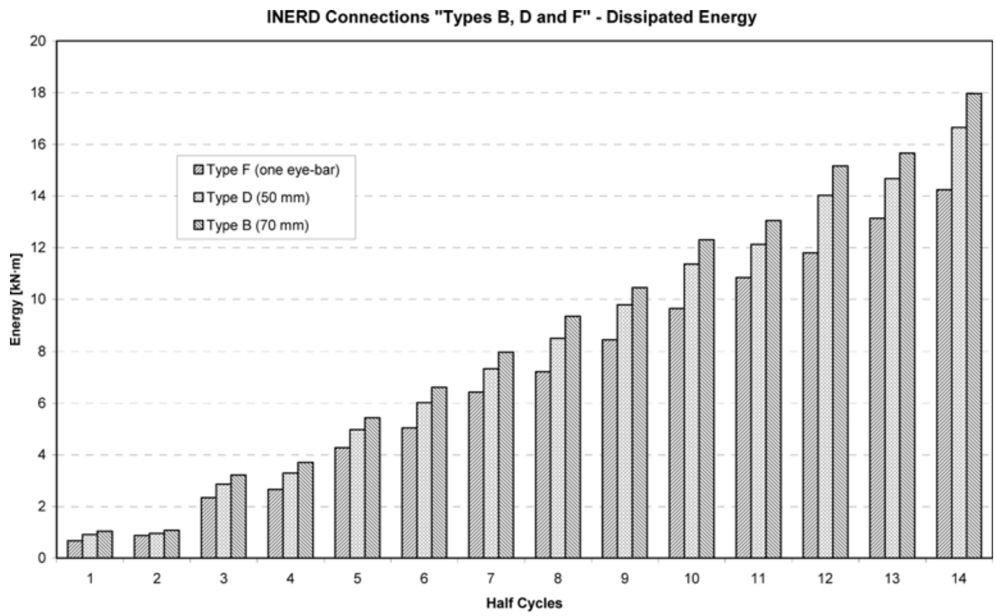


Figure 8. Dissipated energy of connections B, D and F.

up to the formation of two additional plastic hinges at the supports. At that point the system becomes a plastic mechanism and only strain hardening may contribute to any further load increase. The above observations lead to the conclusion that energy dissipation is primarily due to the clamping effect of the external plates (which result in an increase of strength up to 100% of the initial yield resistance) and to a less extend to strain hardening. The parametric studies, see also Fig. 12, indicate that the connection strength above the yield point does not increase linearly with the plate thickness due the clamping effect. Particularly, as the stiffness of the external eye-bars increases, the behaviour of the connection approaches an envelope curve which corresponds to eye-bars of infinite stiffness (i.e. transversal bending of the eye-bars becomes negligible).

For a required level of connection strength the question arises on the best selection of the pin dimensions and material (smaller pin of higher material strength or larger pin with lower material strength?). Figure 13 shows the connection response for different pin materials, which shows that the connection strength is primarily influenced from the pin strength. The results of the parametric studies indicate that it is better to select a smaller pin of a higher strength. However the strength of the pin material should not be higher than that of the plates. Under these conditions, it is recommended to choose thicknesses of the external plates ~0,75 to 1,0 times the smaller

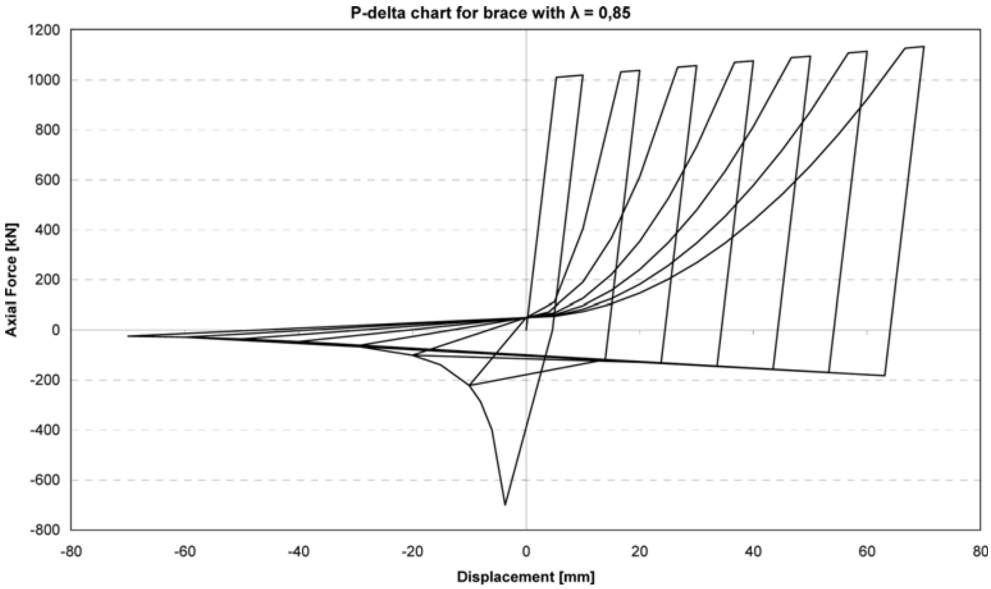
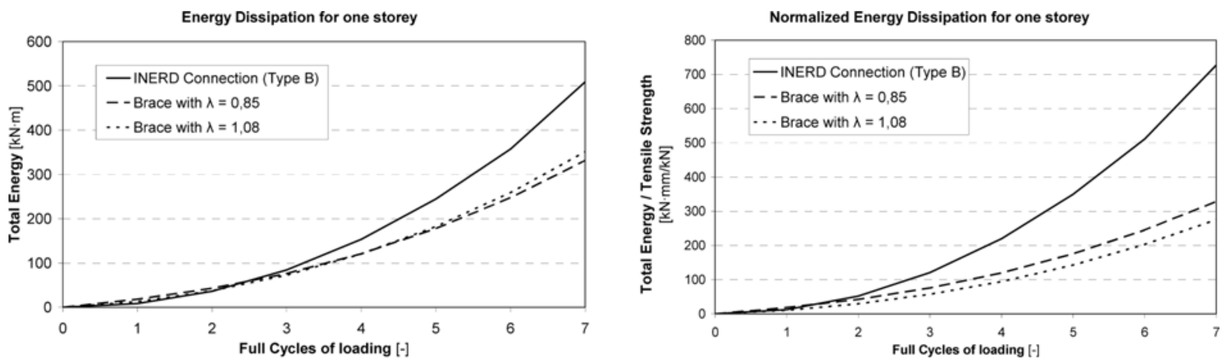


Figure 9. Cyclic response of a single brace.



a) b)

Figure 10. Cumulative dissipated energy for X-braced frames with and without INERD connections.

dimension of the pin section (around which the pin is bent). The thickness of the internal eye-bars may be then set equal to half of the external ones. Of course the plates are dimensioned by application of capacity design criteria for the plates, which require sufficient gross and net section over-strength capacity in relation to the pin.

The tension strength of the connection is, due to transverse bending of the plates, lower than the compression strength. Conversely, the ratio of these strengths provides an indication of the amount of this bending, which, as stated before, influences negatively the cyclic response as it is accumulating for cyclic loading (Fig. 6). However, if the above recommendations for the plate thicknesses are kept, this influence is low and the strength ratio (tension to compression) is above 90%.

By means of engineering models and comparison with the results of the parametric studies, simple formulae appropriate for practical use were derived that allow for the correct prediction of the connection response. Table 3 provides the relevant design formulae for the connection with two internal plates (Fig. 1b) which were validated against the experimental and theoretical results. In addition, the von Mises stresses at Points I and II are shown. Formulae for one internal plate (Fig. 1a) will be proposed as soon as the relevant experimental investigations will be finalized. The proposed formulae, which exhibit an accuracy range of ±5% compared with the parametric studies, are based on following mechanical models:

- Up to the yield load the pin behaves as a beam subjected to four-point bending. The yield load and yield deformation are derived on the condition of the formation of plastic hinges below the load application points. The reduction factor 1,1 on the distance "a" between plates for the yield load represents excessive yielding of the pin within the clear distance between plates (Table 3, stresses at point I). The additional factor 1,5 on the yield displacements represents allowance from holes and the developments of some inelastic deformations.
- The connection strength is derived from the ultimate condition that corresponds to the formation of four

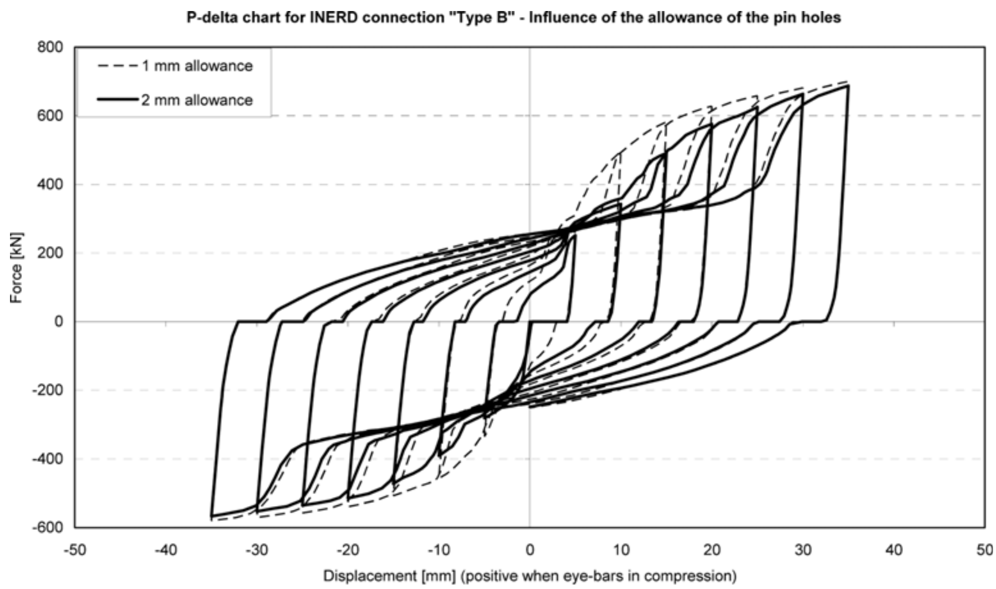


Figure 11. Response of connections B with different allowance for holes.

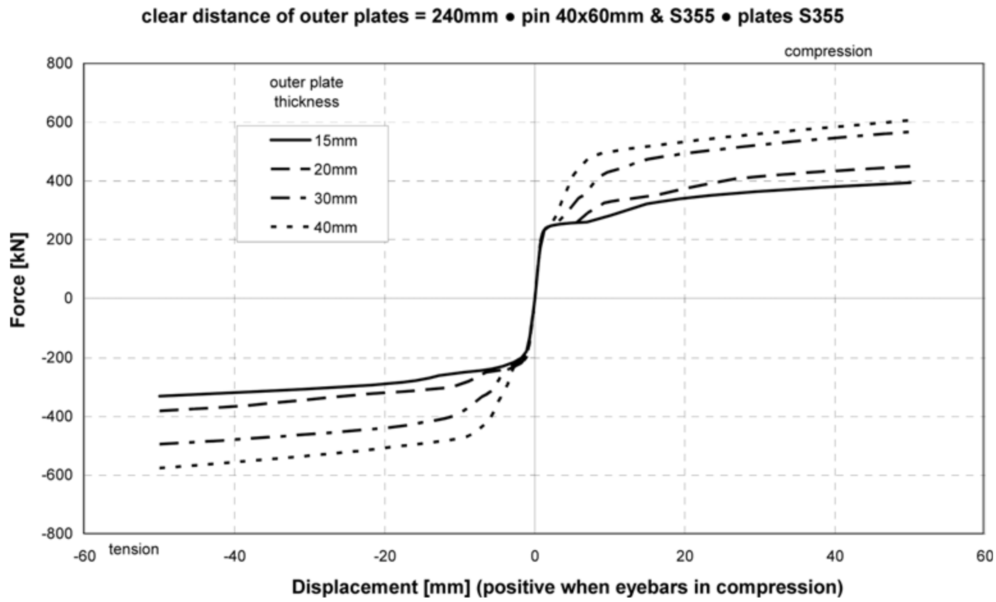


Figure 12. Response of INERD connections for various thicknesses of the external plates ($t_{internal\ plate}$ = 15mm).

plastic hinges in the pin (Table 3, stresses at point II).

- For tension loads, a 10% reduction is proposed due to the increased span caused by the transverse deformations of the plates.
- An over-strength factor of 1,25 is recommended for the capacity design checks of the plates. This excessive strength results in from strain hardening effects at large deformations.
- The deformation capacity of the connection is very high. However a limitation of this capacity to the distance between external and internal eye-bars is recommended.

The design rules for the connection may be summarized as following:

- Connection strength according to Table 3.
- Strength of pin material equal or less than the material of the plates.
- Thickness of external plates 0,75-1,0 times the smaller pin dimension.
- Thickness of the internal plates 0,5 times the thickness of the external ones.
- Connection deformation capacity equal to the clear distance between external and internal plates.
- Allowance for holes in the eye-bars 2 mm.
- Application of capacity design criteria on the connection strength for dimensioning of internal and external plates (over-strength factor 1,25).

As seen in Fig. 1, the pin length is fixed by the height of the column section to which the external plates are attached, or alternatively, by the width of the flanges, if

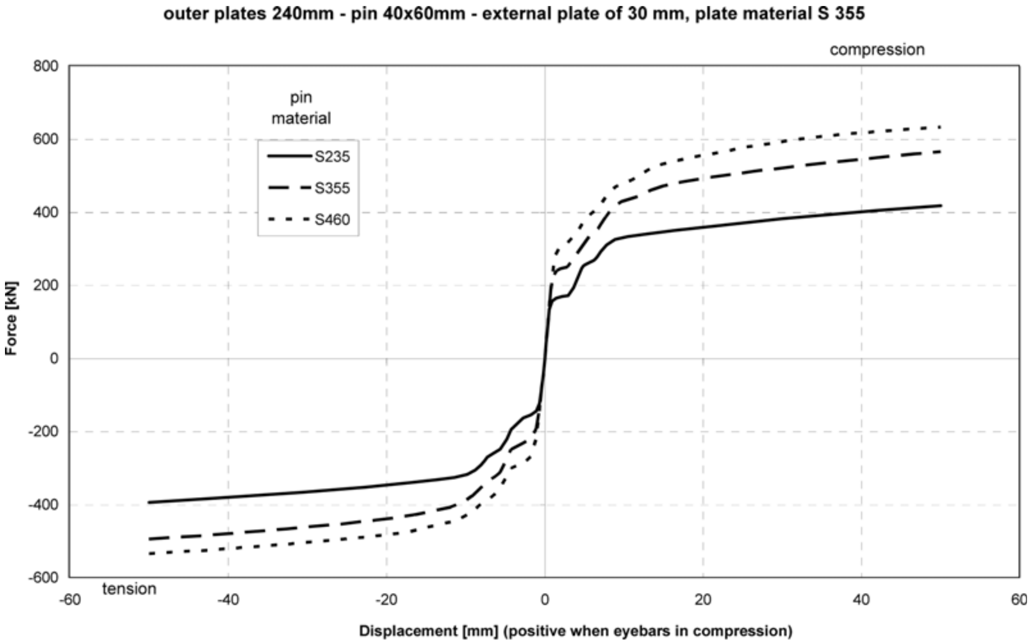


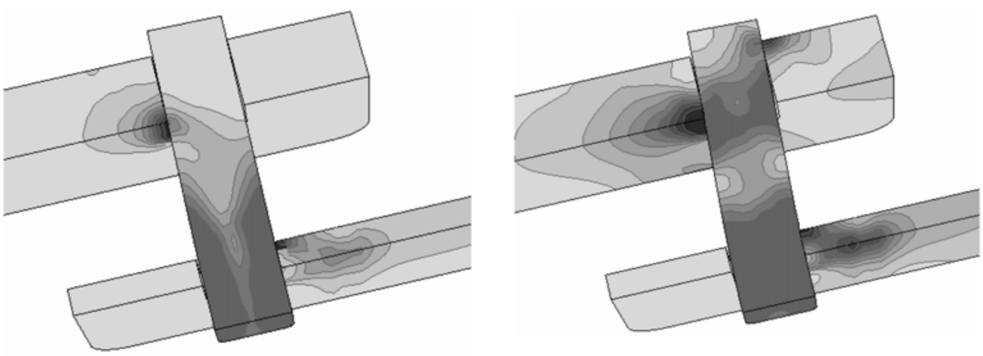
Figure 13. Response of INERD connections for various pin materials ($t_{internal\ plate}$ = 15 mm).

Table 3. Design formulae for the connection with 2 internal plates

	Eye-bars in	Force	Displacement
Point I "yielding y"	Compression	$P_y = \frac{2 \cdot M_p}{(a/1,1)}$	$\delta_y = 1,5 \cdot \frac{M_p}{E \cdot I} \cdot l^2 \cdot \frac{\alpha}{6} \cdot (3 - 4\alpha)$
Point II (Strength) "ultimate u"	Compression	$P_u = \frac{4 \cdot M_p}{a}$	(Deformation capacity = a)
Points I and II	Tension	90% of the above values for P_y and P_u	
Over-strength for capacity design checks		25% beyond P_u	

$M_p = W_{pl} \cdot f_y \quad \alpha = a/l$

l = pin length (axial distance between external eye-bars)
h = pin height
a = clear distance between internal and external eye-bars
f_y = yield stress of pin
W_{pl} = plastic modulus of pin cross section



Stresses at Point I Stresses at Point II the column is turned by 90^0 compared with Fig. 1.

5. Conclusions

Two types of innovative dissipative (INERD) connections, pin- and U-shaped, were developed for seismic resistant braced frames. The connections and more specifically the pins or the U-plates are the dissipative elements of the frames. The advantages of the pin INERD connections for which a priority European Patent Application has been filed may be summarized as following:

- High stiffness for low loads, high ductility for higher loads.
- Protection of braces against buckling.
- All braces, either in compression or in tension, remain active even at large storey drifts.
- Limitation of inelastic action and damage in the pins that may be easily replaced if required.
- Avoidance of brittle fracture and/or low-cycle fatigue.
- Reduction of overall structural costs for the same performance level.

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