Innovative dissipative (INERD) pin connections for seismic resistant braced frames – A state of the art and cost effective low damage technology

Ioannis Prionas[1] and Mark Casey[2]

1. Director of Structural Engineering, Blue Barn Consulting Engineers, Auckland, New Zealand.
   Email: ioannis.prionas@bluebarn.co.nz

2. Structural Engineer, Blue Barn Consulting Engineers, Auckland, New Zealand.
   Email: mark.casey@bluebarn.co.nz

Abstract

Innovative dissipative pin connections have been developed for use in seismic resistant braced frames. The use of these connections prevents the braces from buckling by concentrating the deformations into a yielding pin, dissipating seismic energy. This pin can be easily replaced if required, following a comprehensive condition assessment after a severe earthquake.

This paper presents the results from a joint European Coal and Steel Community (ECSC) research project consisting of a group of 4 European universities, along with design guidelines developed to assist structural Engineers in practice. It also presents the successful implementation of this technology in the first application in New Zealand.

The results from the research as well as from the numerical analysis of our models for the New Zealand project, indicate high energy dissipation capacity for these connections through the flexural yielding of the steel pins. The results also indicate that the potential of brittle failure or low-cycle fatigue is low as the inelastic response is concentrated to the pins and therefore any inelastic action is away from welded connections, bolted connections or other areas of high stress concentration.

Our implementation of the technology in a multi-storey building in New Zealand indicates that this technology enables engineers to efficiently control the damage sustained by buildings during an earthquake, resulting in a cost-effective solution, while at the same time retaining the simplicity of a conventional steel structure.

Keywords: seismic, design, low damage, INERD connections

1 INTRODUCTION

1.1 Energy Dissipative zones in steel frames

Earthquake resistant steel frames are usually designed to dissipate energy. When this occurs, parts of the structure (dissipative zones) exhibit inelastic deformations during strong seismic motions. The main structural typologies (Mazzolani et al., 2000), the corresponding performance characteristics and the expected positions of the dissipative zones are listed in Table 1.

Table 1. Structural typologies and main characteristics for Steel Frames.

	Moment Resisting Frame (MRF)	Concentrically Braced Frame (CBF)	Eccentrically Braced Frame (EBF)	EBF or CBF with INERD connections
Stiffness	Low	High	Moderate	High
Ductility	High	Low	Moderate	High
Dissipative zone	Beam	Braces	Link Beams	Connections

Conventional frames have certain disadvantages in respect to stiffness or ductility. Additional issues related to the seismic performance of those frames are:

- The need for strengthening or replacement of damaged or buckled braces post the Ultimate Limit State (ULS) earthquake with significant disruption and additional costs
- The need for strengthening and repair of the links or the beams that form part of the main gravity system

Damage observed in steel framed structures after recent strong earthquakes indicate the need for improvement of existing structural typologies and the introduction of innovative systems. These systems should aim to have the following properties:

- High stiffness to limit drifts during moderate seismic motions
- High ductility to dissipate energy during strong motions
- Ability for easy and inexpensive repair if required

1.2 Research Background and Development of INERD system

The INERD system was developed and studied during a joint European ECSC 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.

The research of the performance of the new system includes 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)
- Volume with pre-normative design guidelines for innovative devices (European Commission, Research Programme of the Research Fund for Coal and Steel, INNOSEIS, Valorisation of innovative anti-seismic devices)

The results from the full-scale tests as well as from the Computational analysis are available in the international literature. The intention of this paper is to highlight the extensive research completed.

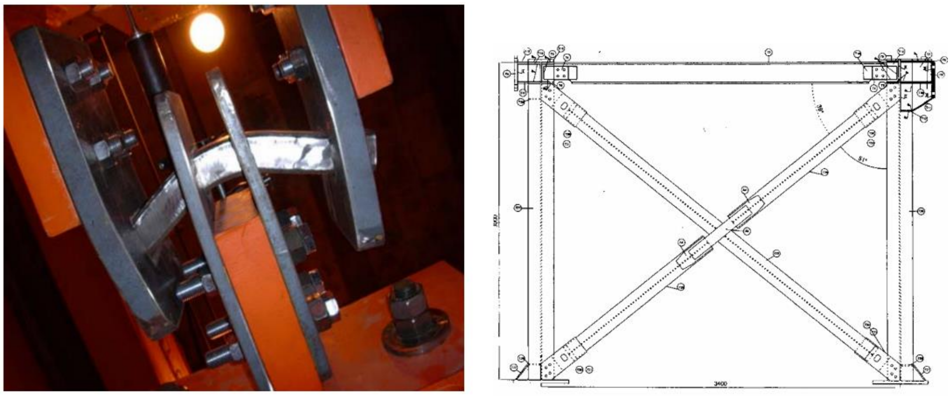

Figure 1: Layout of INERD connections (Vayas et al., 2005)

The pin connection INERD system consists 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 Figure 1. Inelastic deformations and energy dissipation are concentrated in the pins. The pin cross section is not circular to avoid twist around its axis during cyclic loading. Two pin cross sections were selected: a) Rectangular, where the pin is bent around its short side (to prevent lateral buckling), and b) Rectangular with rounded edges, where the pin is bent around its long side.

1.2 Eurocode requirements for the design of braced frames

According to the current European Seismic Code (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 considered". 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 as inactive due to buckling, which evidently leads to heavier brace sections and higher costs. Eurocode also indicates slenderness criteria for the diagonal members which may significantly increase the size of the members.

1.3 New Zealand code requirements for the design of braced frames

The design of concentrically braced frames in New Zealand is currently governed by the requirements of NZS 3404 Section 12.12. Unlike Eurocode 8, NZS 3404 allows for the consideration of both the tension and compression braces under seismic loading, provided the maximum slenderness ratio of the brace does not exceed 120. However, it should be noted that while this maximum slenderness ratio is 120 to consider the compression brace, this value can vary depending on the category of the CBF system and the number of stories of the structure in accordance with section NZS 3404 section 12.12.4.

In addition to slenderness requirements, NZS 3404 also requires the use of a multiplier, C_s, which varies based on the slenderness ratio of the braces and the number of stories the structure contains. This C_s value ranges from 1.0 to 2.1 for Category 1 systems and is applied to the seismic coefficient $C_d(T)$ to effectively increase the seismic actions.

2 DESIGN GUIDELINES FOR INERD CONNECTIONS

2.1 Analytical modelling investigations

The behaviour of the pin connection was studied, during the research programme, by means of three models with various degrees of complexity: a) FEM model, b) Beam model and c) Simple engineering model. The first two have the purpose of better understanding the connection response and to allow for the development of the third engineering model which is intended to be used for design purposes in practical applications.

FEM analyses by means of the general-purpose programme ABAQUS, were performed to study the monotonic and cyclic behaviour of the pin connections. The advantage of the symmetry properties, allows for modelling of one fourth of the complete connection, as shown in Figure. 2. The model dimensions corresponded with those of the specimen for which experimental investigations were performed.

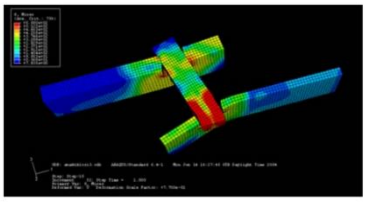

Figure 2: FEM created in ABAQUS (Vayas et al., 2005)

Indicative experimental and numerical results are illustrated in Figure. 3. Forces and displacement are positive when the eye-bars are in compression. It was observed that the analytical rather than the experimental monotonic curves represent the skeleton curves for cyclic loading and that pinching in the hysteretic loops occurs due to holes' ovalisation from bearing stresses. Additionally, no hardening response takes place for cyclic loading due to inelastic transverse bending in the eye-bars and the resistance is bigger for eye-bars in compression than in tension. It was found that there was satisfactory agreement between experimental and numerical results in respect to both local and global behaviour observed. It was also noted that pinching takes place in the analysis at the same yield load level, whereas in the tests at progressively lower levels.

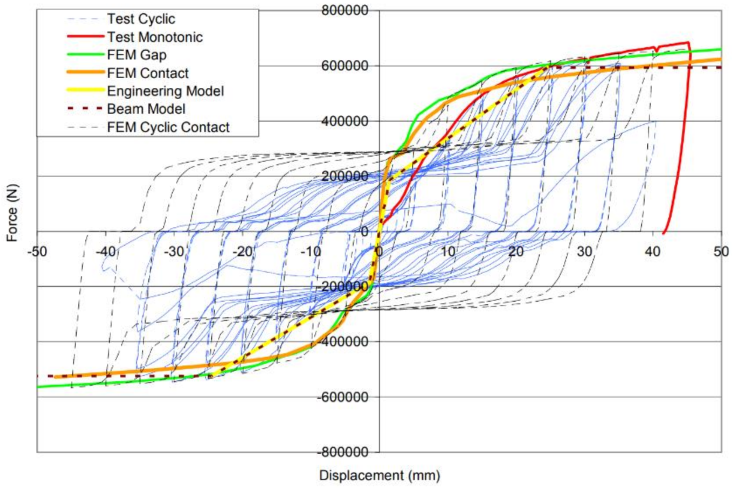

Figure 3: Hysteretic behaviour of INERD connections (Vayas et al., 2005)

2.2 Proposed design guidelines

The research led to the generation of the following design guidelines which can be used for practical applications from structural engineers. These guidelines are intended to supplement the Clauses of the EN-1998-1 in its current version. Please note that all design equations and can be found the INNOSEIS design guidelines written by Vayas et al. (2017.)

Table 2. Upper limit ductility values for global analysis of regular buildings.

INERD pin connection	Ductility Class	
	DCM	**DCH**
At both diagonals ends	3.0	4.0
At one diagonal end	2.0	3.0

To ensure that the dissipative pins will be loaded primarily in bending, their length shall be such that $a>h$ where h is the height of the pin and a is the clear distance between the internal and external plates.

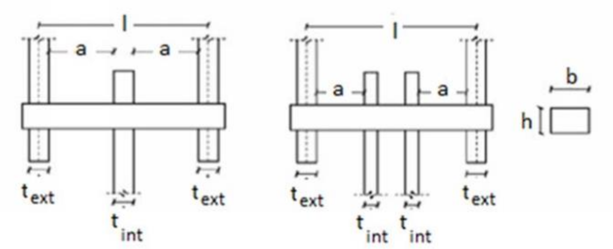

Figure 4: Geometric properties of pinned INERD connection

Concentric braced frames with dissipative pin connections shall be designed in such a way that yielding of the pins in bending will take place before buckling of the braces or yielding of the adjacent members.

For the linear global analysis, the pin connections can be modelled as an axial spring with spring constant. Equation 1 is used for a single internal plate while equation 2 is for a double internal plate

$$K_{pin} = \left(\frac{32.EI}{l^3}\right) \quad (1)$$

$$K_{pin} = \left(\frac{8.EI}{a.l^2.\alpha.(3-4.\alpha)}\right) \quad (2)$$

Where EI = Bending stiffness of the pin; α = a/l

Dissipative pins are designed for the highest brace forces in the seismic design situations. The capacity is calculated accounting for reductions due to the influence of shear and plastic deformation in the pin. The value of β_{iii} is adjusted until the shear capacity and bending capacity of the pin is equal as per equation 3

$$P_{Ed} \le P_{u,Rd} = K_{pin}.\left(\frac{4.M_u}{a_{red}.\gamma_{pu}}\right) = K_{pin}.\left(\frac{2.b.(1-2.\beta_{iii}).h.f_y}{\sqrt{3}.\gamma_{pu}}\right) \quad (3)$$

Where M_u = the ultimate plastic resistance of the pin, β_{iii} = the percentage of each side of the pin that has been subject to plastic deformation with $0 \le \beta_{iii} \le 0.5$.

The overstrength of any pin *i* is defined by equation 4. The selection of a pin's dimensions shall be such that the value of Ω_i is close to 1. In order to achieve a homogeneous global dissipative behaviour of the structure, it should be checked that the maximum overstrength ratio Ω_{max} over the entire structure does not differ from the minimum value Ω_{min} by more than 25% as shown in equation 5

$$\Omega = P_{urd,i}/P_{ed,i}. \quad (4)$$

$$\Omega_{max} / \Omega_{min} \le 1.25 \quad (5)$$

Diagonal members shall be verified to yielding and buckling assuming the exhaustion of the capacity of the pins at their ends as per equation 6

$$N_{Ed} = \Omega_{max} \,.\, P_{u,Rd} \quad (6)$$

Beams and columns connected to braces with flexible INERD connections should meet the following minimum resistance requirement shown in equation 7

$$N_{pl,Rd}\,(M_{Ed}) \ge N_{Ed,G} + 1.1 \,.\, \gamma_{ov} \,.\Omega\, .N_{Ed,E} \quad (7)$$

where Ω is the minimum value of all the pinned connections of the diagonals.

For Non-Linear Pushover Analysis, the following backbone curve is proposed

Point	P	δ_{pl}
A	0	0
B	P_{yd}	0
C	P_{ud}	0.5·h
D	P_{ud}	a
E	0.5·P_{ud}	a
F	0.5·P_{ud}	1.5·a
Acceptance criteria (δ_{pl})		
IO	0.25·h	
LS	0.6·h	
CP	0.8·a	

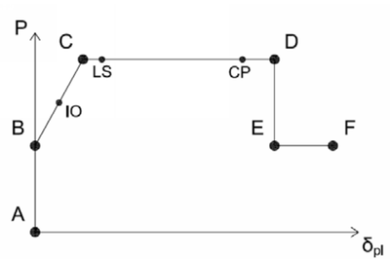

Figure 5: Nonlinear properties of the dissipative pin connection spring (Vayas et al. 2017)

3 NEW ZEALAND CASE STUDY

3.1 Introduction

Harrison Grierson Consultants was engaged by Tauranga City Council to provide structural design services for the Harington Street Transport Hub.

The Harington Street Transport Hub will be a 9-storey building, consisting of 2 basement levels and 7 levels above ground. The floor to floor height of each level is 3.1 meters, however, due to the nature of the ramps in the structure, the building has split levels meaning that the northern and southern ends of the building do not have the same RL at each floor level. The building will have approximate dimensions of 37.2 meters long and 54.7 meters wide.

3.2 Structural System

The primary gravity load structure will consist of the following elements:

- Comflor 80 composite floor decking, supported on secondary composite steel beams.
- Primary steel beams, supporting the composite decking and the secondary composite steel beams.
- Steel columns, providing support to the primary steel beams.

The superstructure of the building will utilise multiple braced bays in both the longitudinal and transverse building directions. The bracing is well distributed and is symmetrical, leading to a regular setout of the lateral load resisting system. These braced bays will transfer the lateral forces down the building through tension and compression forces into the foundation system.

The brace connection also utilises the innovative dissipative technology (INERD) that allows the connections at the end of the braces to yield in a ductile manner and dissipate seismic energy.

3.3 Seismic Analysis

The analysis was conducted using a combination of 2D models and a 3D model, both of which were modelled using ETABS 2016.

The first stage consisted of a response spectrum analysis, which was conducted on both the 2D and 3D models. The worst case was then taken from a comparison of the two models to obtain the design value. This was then followed by a nonlinear static pushover analysis that was conducted in the 2D model only.

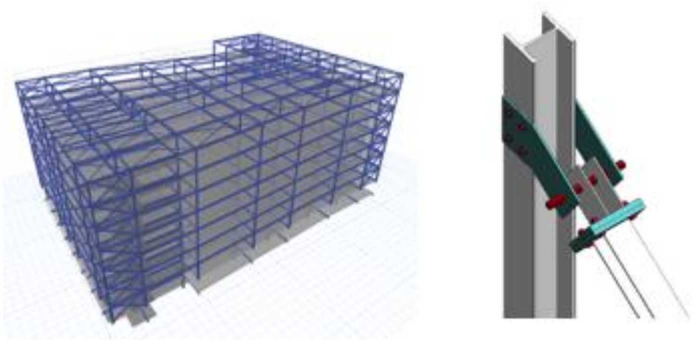

Figure 6: (Left) Computational model from ETABS 2016 (Right) Brace connection used in building

3.4 Analysis Results

In addition to the Response Spectrum Analysis, a Nonlinear Static Pushover Analysis was conducted. The purpose of completing this assessment in addition to the Response Spectrum

Analysis, was to verify the ductility levels of the structure, as a ductility of $\mu = 4$ had been assumed in the design.

This analysis involved pushing the structure to a calculated target displacement value that is representative of an ultimate limit state earthquake. This target displacement was calculated using two methods. The first was the method from ASCE 41-13, and the second was taking the deflections from the Response Spectrum Analysis and multiplying the outputs by the ductility factor of 4 and the required k_{dm} factor from NZS 1170.5. The worst case of the two methods was then used to determine the target displacement for each direction. This resulted in the following target displacement values:

- 186 mm in the Longitudinal direction
- 250 mm in the Transverse direction

The axial hinge properties used in the braces were assigned using the recommendations from the design guidelines as shown in Figure 5. These varied based on the dimensions of the pins and so are different at each location.

As can be seen in Figure 7 below, the INERD connections in both braced frames have been optimised so as to yield uniformly on all levels of the structure in accordance with equation (4) and (5) from section 2.2. This maximises the potential of this type of connection to dissipate seismic energy and avoid concentration of yielding in any locations or storeys. It should also be noted that most of the hinges are in the Immediate Occupancy range (Green) with only a small number of hinges reaching the Life Safety range (Blue) which is acceptable. The results from the pushover analysis also served to validate the choice of μ=4, as the results indicated that much higher levels of ductility could actually be achieved.

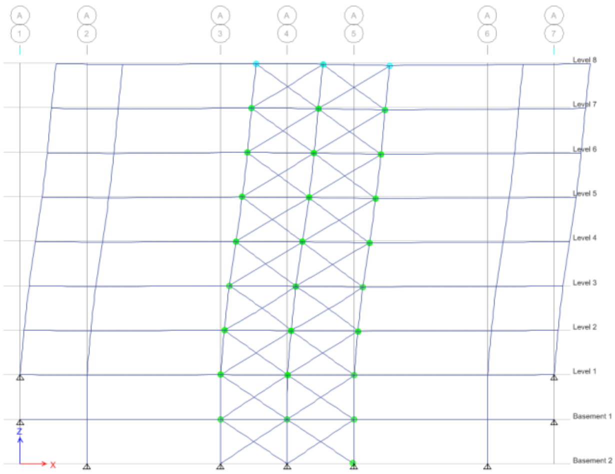

Figure 7: Hinge states from the ETABS model on the transverse frame

3.5 Comparison with the same building designed to New Zealand Design Standard

For comparison purposes, the brace sections and columns adjacent to the braced bays of the Harington St Transport Hub were redesigned using the conventional design procedure as outlined in NZS 3404. As expected, the removal of the INERD connections from the analysis model resulted in a much stiffer structure and a higher calculated base shear. Additionally, due to the slenderness of the brace sections used in the design, a C_s factor of 2.1 was applied to the seismic coefficient, $C_d(T)$, for the analysis. This was done in accordance with NZS 3404 Table 12.12.3(1) for a 7-storey structure.

Due to the significant increase in the forces on the structure, larger sections were required for several braces to meet the required demand. Additionally, as the design axial force on the column is based on the cumulative over-strength capacities of the braces in the bays above, larger brace sections resulted in the requirement for larger column sections, particularly at the base of the structure.

The effect of removing the INERD connections can be clearly seen in the different weights of steel required for the braces and columns adjacent to the braced bays in the two designs. For the two transverse frames the overall difference in the weight of steel was approximately 12700 kg, while the difference in the longitudinal frames was approximately 8300 kg. This amounts to an increase of 32% and 28% for the two directions respectively.

4 CONCLUSIONS

Innovative dissipative pin connections have been developed for use in seismic resistant braced frames. The use of these connections prevents the braces from buckling by concentrating the deformations into a yielding pin which dissipates seismic energy. These pins can be installed either at one end or at both ends of the brace.

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

- Better compliance with the seismic design criteria (high levels of ductility)
- Protection of compression braces against buckling and therefore better control over the damage sustained by the building
- Limitation of inelastic action and damage to small parts of the structure that can be easily replaced, leading to significant cost saving through the design life of the building.
- Avoidance of brittle fracture or low cycle fatigue
- Reduction of overall structural costs for the same performance level in comparison with conventional steel design.

With this technology, any damage during a ULS earthquake will be concentrated at the connections (both ends of braces) which can be easily, and cost effectively replaced. During an SLS event (moderate and more frequent earthquake) the structure will perform almost elastically eliminating the need for repair works.

Our implementation of the technology in a multi-storey building in New Zealand indicates that this technology enables engineers to efficiently control the damage sustained by buildings during an earthquake, resulting in a cost-effective solution, while at the same time retaining the simplicity of a conventional steel structure.

5 ACKNOWLEDGEMENT

We would like to express our appreciation to Professor Ioannis Vayas who is one of the generators of the INERD system and provided us with the design guidelines and very useful comments. We would like also to thank Harrison Grierson for allowing the use of the Harington Street Transport Hub as a case study and James Knight, Senior Structural Consultant, for providing peer review services on this project.

6 REFERENCES

Calado, L. & Ferreira, J. 2004. INERD Connections. Technical Report, Lisbon. IST Lisbon

Castiglioni, C. Crespi, A. Brescianini, J. & Lazzarotto, L. 2004. INERD Connections, Technical Report, Milan. Politecnico Milano

European Convention for Constructional Steelwork (ECCS). 1986. Recommended testing procedure for assessing the behaviour of structural steel elements under cyclic loads. Rotterdam: ECCS Publ. No 45

EN 1998, Eurocode 8 Design of structures for earthquake resistance. CEN, European Committee for Standardisation, 2004

Mazzolani, F. & Gioncu, V. 2000. Seismic Resistant Steel Structures. Springer Verlag

NZS 3404 Parts 1&2 1997

Vayas, I. Thanopoulos, P. & Dasiou, M. 2004. INERD Connections. Technical Report, Athens. NTU Athens

Vayas, I. Thanopoulos, P. 2005. Innovative Dissipative (INERD) Pin Conections for Seismic Resistant Braced Frames, International Journal of Steel Structures, Vol 5 No. 5: 453-464

Vayas, I. Thanopoulos, P. 2006. Dissipative (INERD) Verbindungen für Stahltragwerke in Erdbebengebieten, Sthalbau, Vol 75: 993-1003

Vayas, I. Plumier, A. Castiglioni, C. & Calado, C. 2005. Behaviour of Seismic Resistant Braced Fames with Innovative Dissipative (INERD) Connections

Vayas, I. Pavlos, T. Panagiotis, T. 2017 INNOSEIS: Valorisation of Innovative Anti-Seismic Devices, European Commission Research Programme of the Research Fund for Coal and Steel, Work Package 3 – Deliverable 3.2