An Experimental and Numerical Investigation of the Seismic Response of Plan Irregular Multi-Storey Concentrically-Braced Buildings

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SUMMARY:
The seismic response of plan irregular multi-storey steel braced framed structures is investigated using full-scale inelastic dynamic testing combined with numerical modelling. The dynamic testing comprises substructured hybrid tests, in which the first storey of the critical braced frame in the irregular structure is physically tested, while the response of the remainder of the structure is simultaneously modelled. Employing an OpenSees model validated against these experimental hybrid test results, a parametric investigation of the seismic response of plan irregular multi-storey braced frame structures is performed using nonlinear time history seismic analysis. The parametric study consists of an examination of the important factors affecting the seismic response of plan irregular braced structures, including static eccentricity and lateral torsional frequency ratio. The seismic response parameter is storey displacement ductility demand which is closely related to the critical response quantity of brace member deformation ductility demand.

Keywords: hybrid testing, numerical modelling, plan irregular, braced frames, ductility demand

1. INTRODUCTION

Concentrically braced frame steel structures offer high lateral stiffness and good hysteretic response to cyclic loading, combined with an efficient use of structural materials. While the inelastic response of these systems can be modelled accurately, the seismic response of plan irregular braced structures includes a torsional component, making prediction of their seismic behaviour more difficult. Uneven distributions of mass or stiffness lead to an asymmetric deformation demand, including the concentration of local inelastic deformations in a limited number of bracing members and frames. Irregular building structures display a non-uniform response due to a non-uniform distribution of structural properties. Plan irregularity arises due to stiffness and/or mass eccentricity in the structure, causing the response of the structure to be not only translational, but also torsional (De Stefano and Pintucchi, 2001). In-plan static eccentricity, e_s is defined as the distance between the Centre of Mass (CM) and Centre of Resistance (CR) of the structure at each floor (see Figure 1), and structures are therefore either torsionally balanced (with no static eccentricity, e_s) or torsionally unbalanced (with a static eccentricity, e_s).

There remains a lack of agreement on how the best design guidance for plan irregular structures. Pinto et al (2007) state that consensus is lacking in regard to design against natural or accidental torsion, and that numerical modelling studies are required to assess the guidance provided in Eurocode 8 (2004) (EC8). In early research on the seismic response of plan irregular structures, simplified single-storey models were employed because they could be easily parameterised and the influence of structural factors on the seismic response could be directly quantified (Tso and Bozorgnia, 1986; Goel, 1997; Ghersi and Rossi, 2001). The relatively simple computation required for these single-storey models and the reduced number of influencing parameters compared to more complex structural systems were attractive to researchers. In more recent years, however, with the increase in computational power and greater availability of three-dimensional non-linear finite element software, investigations of the seismic response of more detailed multi-storey plan irregular structures have received a greater level of attention. Some research has investigated the extension of results based on single-storey models to multi-storey structure (Fajfar et al 2005), while other research has investigated more realistic multi-storey framed structures (Stathopoulos and Anagnostopoulos, 2005). In any structure, stiffness, mass or strength eccentricity may exist in two orthogonal directions rather than just an idealised single direction. Early idealised single-storey models with resisting elements in one direction only neglected some of the important effects that may influence the inelastic response of the resisting elements. While some researchers have since found that bi-directional effects are significant during the torsional response of a plan irregular structure (Heredia-Zavoni and Machicao-Barrionuevo, 2004; Peruš and Fajfar, 2005) others have found these effects to be not significant (Ghersi and Rossi, 2001; Stathopoulos and Anagnostopoulos, 2003).

Although little previous research has been conducted into plan irregular concentrically braced frame structures, the inelastic deformation capacity of some brace member types (such as hollow section steel members) is known to be limited (Goggins et al, 2006). Limits on member and cross-section slenderness are required to ensure that these bracing members can act as dissipative elements without fracturing. While these limits may be adequate for torsionally balanced structures, it is not known whether they are sufficient for the greater brace ductility demand that may be experienced in torsionally unbalanced buildings. This paper describes an analytical and experimental investigation into the ductility demands experienced by braced frame plan irregular structures undergoing torsional seismic response. The aim is to develop accurate and experimentally validated numerical models suitable for parametric studies leading to improved design guidance.

2. BRACED PLAN IRREGULAR STRUCTURAL MODEL

2.1 Structural Layout

The two-by-one bay, three-storey concentrically braced framed steel structure shown in Figure 1 is investigated. The structure has been idealised to investigate the generic response of braced frames and to avoid case specific results. As can be seen in Figure 1, the two end frames of the structure are braced in the x-direction, while the central frame is unbraced. All column members have 203 x 203 x 46mm UC cross-sections, while the beam members possess 305 x 165 x 40mm UB cross-sections. The structure has a 2.5m high first storey, a 2.2m high second storey and a 2.2m high third storey, in agreement with the dimensions of the experimental model described later and common architectural proportions. The bracing system consists of concentric X-bracing with square hollow steel braces joined to the beam and column members using flexible gusset plate connections (Figure 2).

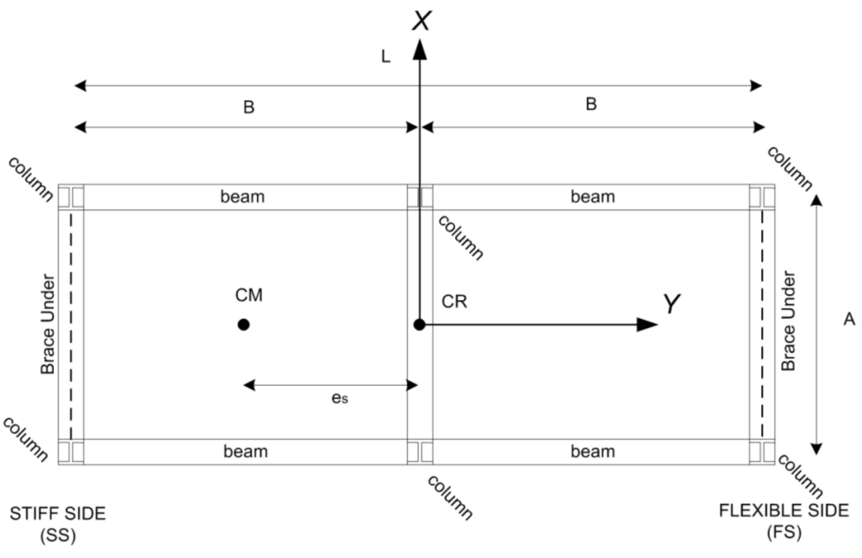
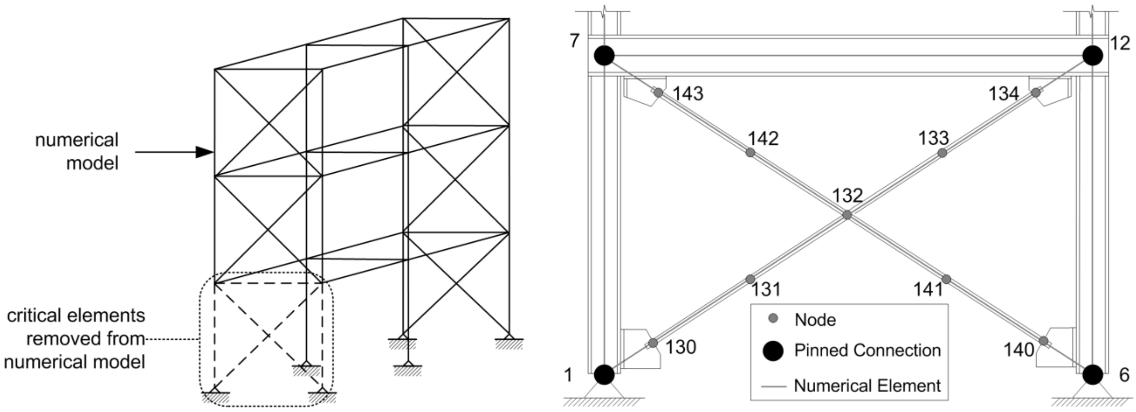


Figure 1. Plan view of plan irregular steel braced frame structure model.

2.2 Numerical Model

The concentrically braced framed structure was modelled using OpenSees (McKenna et al, 2000) (Figure 2). The column members are modelled as nonlinear beam-column elements with 7 No. integration points along their length and subdivided across their section into 10 elements along each thin-walled section and 5 elements across each thin-walled section. The beam members are modelled with elastic beam column elements with relevant section properties. The brace members are modelled as nonlinear beam-column elements with 7 integration points along their length with their cross-section depth and width subdivided into 10 and 5 fibres, respectively. An out-of-plane camber is applied to the longitudinal profile of the brace members, representing expected geometric imperfections and ensuring accurate modelling of global member buckling. The initial out-of-plane camber has an amplitude equal to 0.1% of brace member length (at e.g. nodes 131, 133, 141 & 141 in Figure 2(a)), as suggested by Uriz et al (2008).

The gusset plate brace connections were modelled as elastic beam-column elements with a relatively high stiffness, representing the actual stiffness of the gusset plates in the experimental model described later. The mass of the structure is represented by lumped masses at the structural nodes, and the proportions of these are varied to obtain different building torsion characteristics. Mass proportional Rayleigh damping is used to numerically represent the application of damping to the physical system.



(a) (b)

Figure 2. (a) 3D view of model structure with critical elements and (b) numerical modelling of test substructure.

2.3 Key Structural Parameters

One of the aims of the investigation was to assess the influence of key structural parameters affecting the ductility demand in plan irregular braced framed steel structures. These parameters are the lateral torsional frequency ratio, Ω_θ, and the mass eccentricity, e_s. Ω_θ is an important parameter because if Ω_θ <1, the structure is classified as torsionally flexible and if Ω_θ >1, the structure is classified as torsionally stiff. Ω_θ is defined as $\Omega_\theta = r_k / r_m$, where; r_k = stiffness radius of gyration about the centre of resistance; and r_m = mass radius of gyration about the centre of mass.

The maximum e_s value investigated is $0.15L$ (refer to Figure 1), as higher levels are unlikely to occur in real structures. The lower and upper bounds of Ω_θ are set at 0.75 and 1.25 respectively, representing the realistic range of torsional flexibility/stiffness. The influence of the plan aspect (PA) ratio (where the PA ratio = length of building/width of building) and the effects of bi-directional loading are also investigated. A reference structural model designed for $e_s = 0.0L$ (no static eccentricity), has a PA ratio of 2.0, $\Omega_\theta = 1.0$ (neither torsionally flexible or stiff) and employs 30x30x3mm SHS bracing (= 1.68) in both the SS and FS braced frames.

3. HYBRID TESTING

3.1 Hybrid Test Method

To validate the numerical modelling of the plan irregular structure presented in Section 2, an experimental investigation was undertaken using the hybrid test method. The hybrid test method combines physical testing with simultaneous numerical modelling to execute simulations of dynamic response using a time-stepping routine. The hybrid test method developed from the pseudo-dynamic (PsD) method, the concept of which was first proposed by Hakuno, et al. (1969) and was further developed by Takanashi et al. (1975) and Shing and Mahin (1984). Typically in a hybrid test, the important component of the structure being analysed is physically tested using high speed actuators (physical substructure) and the rest of the structure is numerically modelled (numerical substructure). A time-stepping solution procedure employing a numerical integration algorithm is employed. At each time step, key measured displacements and forces in the experimental substructure are fed back from the experimental hardware to the numerical model. These results are then used to solve the equation of motion for the command displacement at the next time step. This test procedure was implemented using a generic hybrid simulation framework employing the communication protocol OpenFresco (Open Framework for Experimental Setup and Control) (Schellenberg A, et al, 2009). The development of OpenFresco has been has been closely linked to that of OpenSees, which is employed to model the numerical substructure in the hybrid tests presented here.

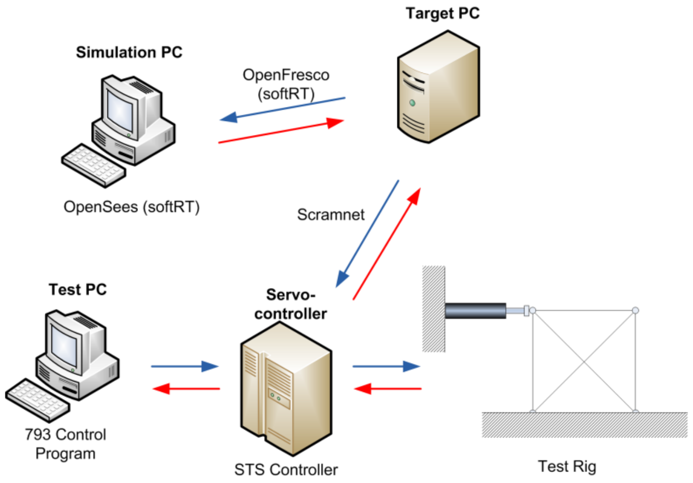


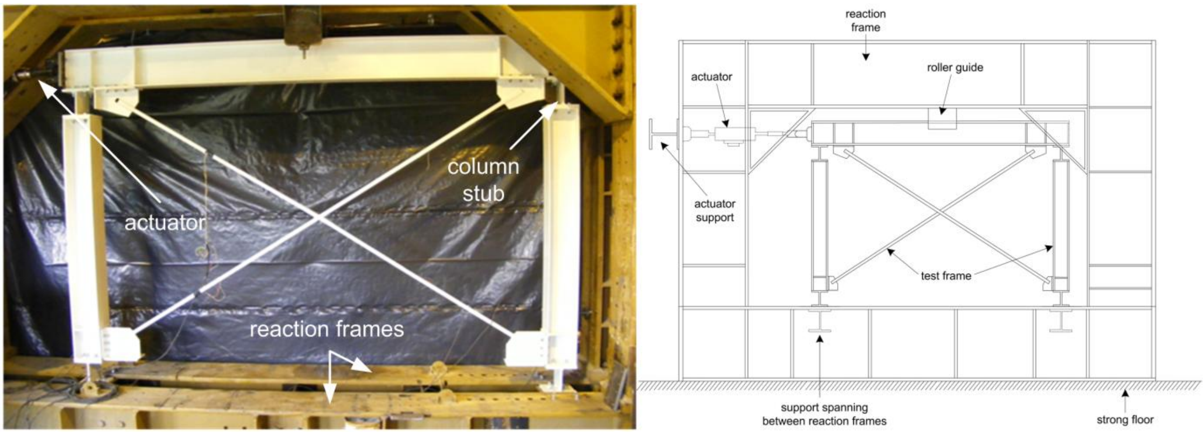
Figure 3. Schematic of hardware and data communication for a soft real-time hybrid test.

The hybrid testing facility at Trinity College Dublin comprises an MTS real-time hybrid test system. The data communication in a soft real-time hybrid test is shown in Figure 3. The hardware consists of a Series 111 MTS Accumulator and a high speed linear hydraulic actuator with a 150kN capacity and 250mm (±125mm) stroke. The computer hardware comprises a Simulation Host PC, a Real-time Target PC, a Test PC and a two-channel MTS 493 Real-time Controller. The digital controller has closed loop PID control. The Structural Test System (STS) software provides the user interface for PID control and calibration of the actuator.

OpenSees is used to create the dynamic simulation model of the numerical substructure. The structural model is created on the Simulation PC and then downloaded onto the Target PC through a fibre optic cable, as indicated in Figure 3. The sole task of the Target PC is to run the model in real-time using Mathworks xPC Target. The Target PC has no user interface and receives commands directly from the Simulation PC. The Target PC sends commands to the Structural Test System (STS) controller via the shared reflective memory SCRAMNet GT150 (Shared Common Random Access Memory Network). OpenFresco is the middleware that supports communication between the finite element software and the experimental hardware. The Test PC provides the user interface to the servo-controller and allows tuning and control of the actuator through a PID controller. In each time-step, the command displacement is sent from the servo-controller to the MTS actuator. The resulting measured force and displacement are returned to the servo-controller and then back to the Target PC, where the data is used to calculate the next time step command displacement, making the process close-looped.

3.2 Test Set-up

Experimental Substructure: Preliminary numerical modelling of the three storey plan irregular concentrically braced structure shown in Figure 1 indicated that the SS of the structure at first-storey level is subjected to the greatest seismic displacement and ductility demand. This part of the structure therefore experiences the most nonlinear response and is critical to the overall response of the structure as a whole. Hence in the hybrid tests, as indicated in Figure 3, this part of the structure is removed from the OpenSees numerical model to become the experimental substructure. The test set-up for this substructure can be seen in Figure 4. As shown in Figure 4 (a) & (b), the actuator is located at the top left hand corner of the frame, and the test model is mounted between two side-by-side reaction frames. Simplified flexible connections, designed to ensure the stability of the hybrid test procedure, are used to represent the pinned connections at either end of the column members.



(a) (b)

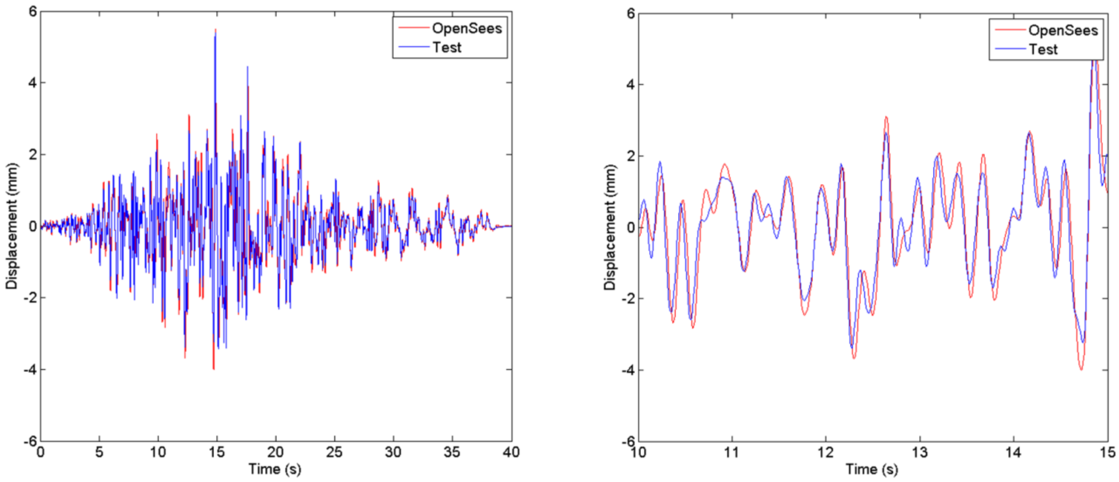
Figure 4. Experimental set-up: (a) photograph and (b) schematic.

Experimental Programme: The aim of the test programme was to assess the affect of Ω_θ, and e_s and the EC8 accidental eccentricity provision on the seismic response of braced plan irregular structures and to provide test data for numerical model validation. Full details are provided by McCrum (2012). In this paper, only the influences of Ω_θ, and e_s on ductility demand are considered. These parameters were varied by altering the properties of the numerical model alone.

3.3 Hybrid Test Results

The torsional stiffness of the structure was observed to have a substantial influence on the peak lateral displacement of the torsionally stiff (Ω_θ = 1.25) and torsionally flexible (Ω_θ = 0.75) structures. For example, a torsionally flexible test structure with Ω_θ = 0.75 experienced a maximum lateral roof displacement of 27.1mm, whereas an equivalent torsionally stiff test structure with Ω_θ = 1.25 experienced a maximum lateral roof displacement of only 5.5mm. Two other equivalent test structures with Ω_θ = 0.75 and 1.25 experienced maximum lateral roof displacements of 22.7mm and 5.1mm, respectively.

Figure 5 compares the observed time history of lateral displacements with the response of the OpenSees model for a test structure with 30x30x3mm SHS (= 1.68) brace sections, Ω_θ = 1.25, e_s = 0.15*L* and a PA ratio of 2.0. The structure was subjected to the Taiwan ground acceleration history scaled by a factor of 2.0. The test performed was a slow continuous hybrid test with the extended timescale resulting in 95% of the simulation steps not having to slow down or hold the actuator, similar to hybrid tests performed by Stojadinovic et al (2006). As can be seen in Figure 5, the displacement response of the test structure is modelled accurately using OpenSees. In total, 24 hybrid tests were undertaken as part of the testing programme. Across all tests, the average error between the modelled and measured lateral roof displacements was 4%, while the average error for in lateral roof acceleration was 9%. Strain gauges were placed at mid-span of the brace members on the top and back face of the section; the average error between modelled and observed strains was 20% (McCrum, 2012). Similar comparisons between the simulated and observed responses were achieved for the other experiments, indicating that the OpenSees model is capable of predicting the inelastic seismic response of this structural form. The numerical model results did display some overestimation of stiffness when compared to the test data. More detailed inspection of the test results confirm that the slow continuous hybrid test had been implemented successfully with limited tracking error.



(a) (b)

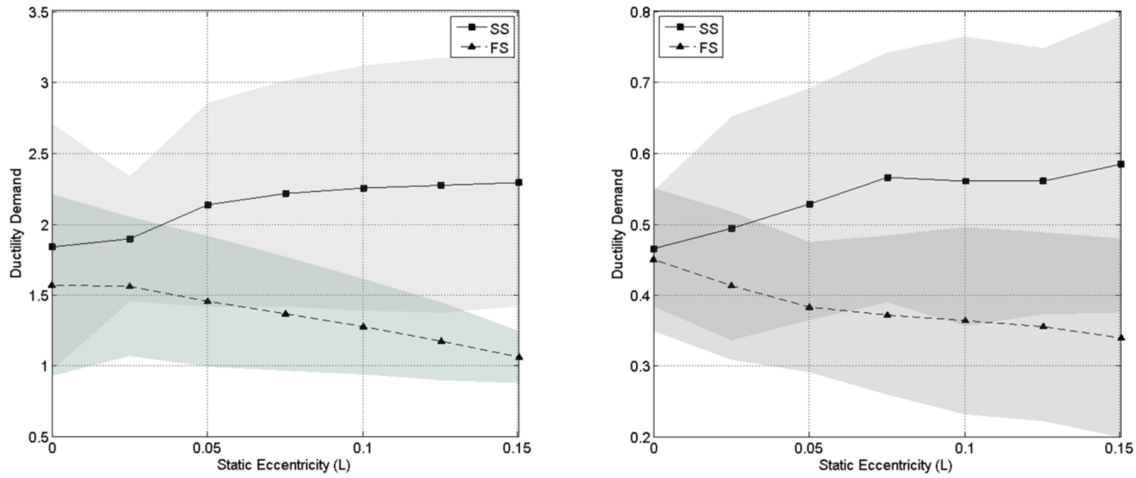
Figure 5. Sample hybrid test results: (a) Modelled (OpenSees) and measured (Test) first-storey lateral roof displacement response (b) comparison of responses between t = 10 and 15 seconds.

4. PARAMETRIC STUDY RESULTS

The validated OpenSees model of the three storey building is employed in a parametric study of the influence of key structural parameters on the response of plan eccentric braced frame structures. The properties of the model are varied to obtain different static eccentricity and torsional frequency ratios, and its response to the five different ground accelerations is determined using three-dimensional inelastic time-history analyses. The earthquake records employed were El Centro (1940), Friuii (1976), NW California (1951), Taiwan (1986) and Spitak (1988). The obtained results are normalised by the response of the reference model structure, which has a PA ratio of 2.0, Ω_θ = 1.0, e_s = 0.0L and 30x30x3mm (= 1.68) bracing throughout. The reference structure has not been designed to resist any torsional effects, has no mass eccentricity and is neither torsionally stiff nor torsionally flexible. The presented results are the average response to the set of five accelerograms, all scaled to a PGA = 0.315g. The maximum displacement ductility demand is used to assess performance, and is defined as $\mu_\delta = \delta_u / \delta_y$, where δ_u is the maximum displacement response of the SS or FS braced frame and δ_y is the first yield displacement of the structure. This response variable is important because it directly corresponds to the axial deformation ductility demand experienced by the brace members.

4.1 Static Eccentricity

Figure 6(a) and (b) illustrate the variations in SS and FS ductility demand with static eccentricity, e_s, for torsional frequency ratios of Ω_θ = 0.75 (torsionally flexible) and 1.25 (torsionally stiff), respectively. The different responses of the torsionally flexible and torsionally stiff structures are evident. Both sides of the torsionally flexible structure are subjected to much greater (in the order of 4 times) ductility demands than the torsionally stiff structure. While the SS ductility demand increases with e_s, the FS ductility demand reduces.



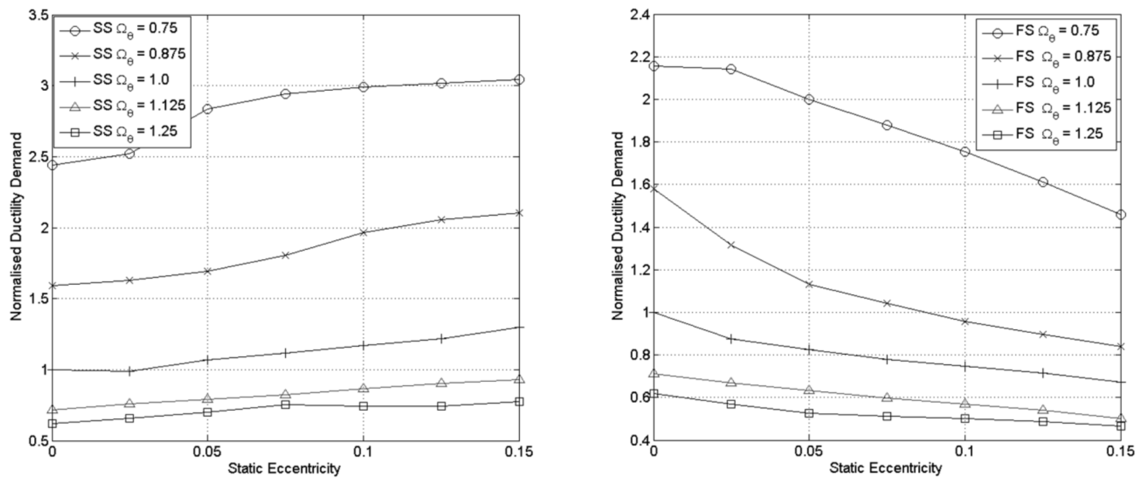
(a) (b)

Figure 6. Variation of SS & FS ductility demand with static eccentricity for (a) $\Omega_\theta = 0.75$ and (b) $\Omega_\theta = 1.25$. Plotted curves and shaded areas represent mean response and 95% confidence intervals for five accelerograms,

4.2 Lateral Torsional Frequency Ratio

The effect of varying the lateral torsional frequency ratio is presented in Figure 7. Analysis was undertaken on a concentrically braced plan irregular structure with a PA ratio of 2.0 and = 1.68, with a range of static eccentricities and lateral torsional frequency ratios.

Figure 7(a) illustrates the variation in SS normalised ductility demand with static eccentricity, e_s, for a range of lateral torsional frequency ratios, Ω_θ. The results displayed in Figure 7 are mean values for the five earthquakes considered. Ductility demand is observed to be very sensitive to Ω_θ. While the torsionally stiff structures ($\Omega_\theta = 1.125$ and $\Omega_\theta = 1.25$) perform better than the reference structure (with normalised ductility demands less than 1.0 for all levels of static eccentricity), the torsionally flexible structures ($\Omega_\theta = 0.75$ and $\Omega_\theta = 0.875$) experience greater ductility demands than the reference structure. The SS normalised ductility demand of the most torsionally flexible structure with $\Omega_\theta = 0.75$ is on average 2.83 times that of the reference structure. The increase in ductility demand with e_s observed in Figure 6(a) is displayed for all values of Ω_θ. Figure 7(b) shows that torsionally flexible structures also experience substantially increased FS ductility demands, but in this case the ductility demand reduces with e_s, and the largest observed value (at $\Omega_\theta = 0.75$) is less than the largest observed value on the SS of the structure.



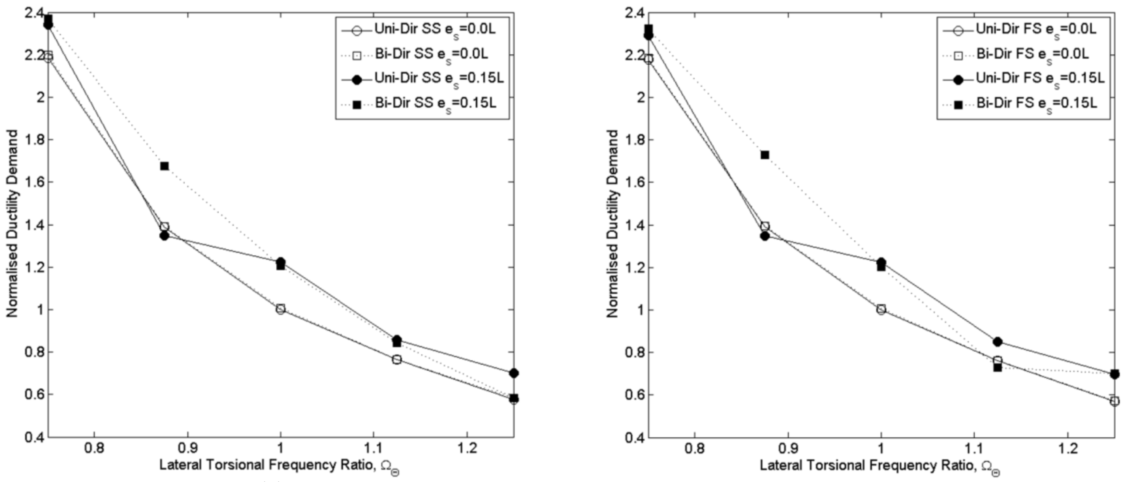
(a) (b)

Figure 7. Variation of normalised ductility demand with static eccentricity for varying levels of lateral torsional frequency ratio on (a) SS and (b) FS.

4.4 Uni- and Bi-directional Seismic Excitation

The influence of bi-directional seismic excitation was investigated by subjecting the plan irregular braced structure to two orthogonal ground motions. Structures with a PA ratio of 1.0, a brace section size of 30x30x3mm SHS (= 1.68) in both orthogonal directions and a range of Ω_θ and e_s values were analysed. The static eccentricity was applied in one orthogonal direction only and a PA ratio of 1.0 was employed to ensure identical vertical plane frame systems in both horizontal directions. These conditions allow direct comparison of the effects of uni-directional and bi-directional excitation.

The obtained results are presented in Figure 8, normalised by the response of a uni-directional excited structure with a PA ratio of 1.0,   = 1.68, $\Omega_\theta = 1.0$, $e_s = 0.0L$ and bracing in the direction of excitation only. Similar behaviour is observable on the SS and FS of the structure, and both plots suggest that the application of bi-axial excitation leads to greater ductility demand in this class of structure. The results indicate some variation with Ω_θ and e_s, but the demand with bi-directional excitation is often 20-30% higher than the demand observed when the same structure is subjected to uni-directional excitation.



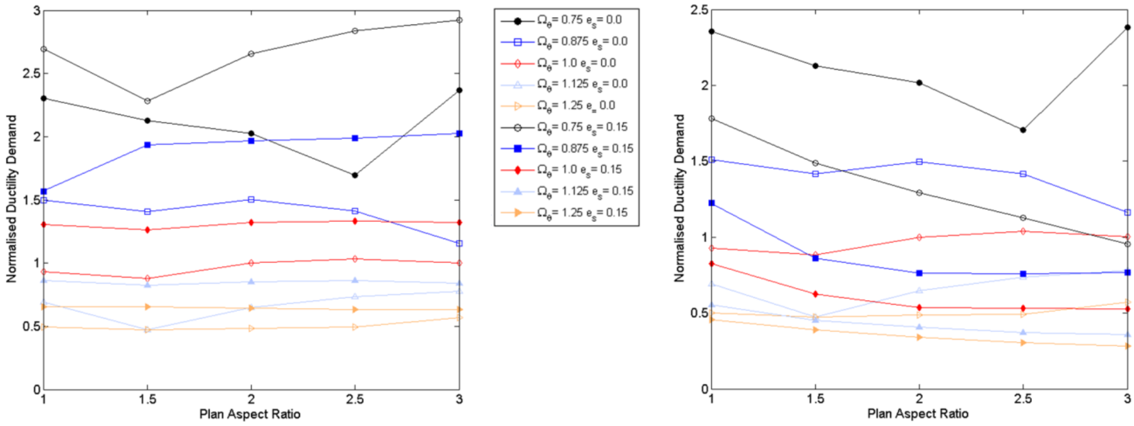
(a) (b)

Figure 8. Variation in (a) SS and (b) FS ductility demand with Ω_θ for uni- and bi-directional excitation

4.5 Plan Aspect Ratio

The influence of the PA ratio on the seismic behaviour of concentrically braced plan irregular structures is investigated by analysing the response of model structures with PA ratios of 1.0, 1.5, 2.0, 2.5 and 3.0. The properties of the concentrically braced frames in these models are   = 1.68, $e_s = 0.0L$ and $0.15L$ and the PA ratio is varied by increasing/decreasing the dimension of the structure perpendicular to these braced frames. The width of the braced frames remains unchanged and the lateral torsional frequency ratio, Ω_θ, is varied between 0.75 and 1.25. Results are normalised against the base model structure with a PA ratio of 2.0, $\Omega_\theta = 1.0$, $e_s = 0.0L$ and   = 1.68.

The results of these analyses are displayed in Figure 9, where the response of the different models has been normalised by the response of the reference model structure with a PA ratio of 2.0, $\Omega_\theta = 1.0$, $e_s = 0.0L$ and   = 1.68. The results indicate that the PA ratio does not have a large effect on the ductility demand experienced on either side of the structure. There is a general trend of increasing SS ductility demand and decreasing FS ductility demand for larger PA ratios, and the strongest effect occurs at the higher e_s value. The normalised ductility demand remains approximately constant for all levels of PA ratio for no static eccentricity.



(a) (b)

Figure 9. Variation of normalised ductility demand with plan aspect ratio on (a) SS and (b) FS of the structure.

5. CONCLUSIONS

This paper has presented a combined hybrid testing and numerical modelling investigation of the deformation demands experienced by multi-storey plan irregular concentrically braced steel structures. Particular emphasis was placed on displacement ductility demand as this is directly related to the axial deformation ductility demand in individual brace members, which is often the limiting seismic response parameter for this class of structure. Substructured slow continuous hybrid tests were performed on a set of three-storey plan irregular model brace frames. The obtained hybrid test results were used to validate an OpenSees numerical model of the structure, by demonstrating close agreement between the global displacement responses obtained in hybrid tests (in which the actual nonlinear response of the most deformed bracing members is observed online) and in purely numerical simulations (in which brace member behaviour is modelled using available features within OpenSees) and whose properties were then varied in a parametric study of the more general response of irregular concentrically braced steel structures. This comprised the use of inelastic time history analyses using a range of earthquake records scaled to different values.

The results obtained in the parametric study confirm that the static eccentricity, e_s, and the lateral torsional frequency ratio Ω_θ, are important parameters influencing displacement and ductility demand in plan irregular braced frame structures. The SS of the structure is subjected to greater ductility demand than the FS of the structure. For all values of Ω_θ, ductility demand increases with increasing levels of static eccentricity on the SS of the structure and reduces with increasing levels of static eccentricity on the FS of the structure. The ductility demand on the SS of a highly torsionally flexible structure (Ω_θ = 0.75) was observed to be nearly 4 times greater than that observed in a highly torsionally stiff structure (Ω_θ = 1.25). On average, torsionally flexible structures experienced ductility demands that were 3.75 times those experienced by comparable torsionally stiff structures.

The results obtained from a limited study indicate that bi-directionally and uni-directionally excited structures experience similar levels of deformation demand. The uni-directionally excited structure slightly overestimates the ductility demand and interstorey drift for high levels of static eccentricity. Variations in the plan aspect ratio were not observed to have a significant effect on the seismic deformation demand.

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