Analytical modelling of jointed precast concrete beam-to-column connections with different damping systems

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ABSTRACT: Jointed precast concrete systems typically have low inherent damping and are thus particularly suitable for applying supplemental damping systems. Analytical modelling is utilised to characterise jointed beam-to-column rocking connections, using a rate-dependent tri-linear compound version of the well-known Menegotto-Pinto rule. The analytical model is verified against near full-scale experimental results. The beam-column connections are constructed utilising Damage Avoidance Design (DAD) principles with unbonded post-tensioned tendons. High force-to-volume extrusion-based energy dissipaters are externally fitted to provide supplemental energy dissipation and modify joint hysteretic performance. Multiple joint configurations are analysed, with supplemental damping systems modified to investigate the effect of damping forces on joint hysteresis. Particular attention is given to the re-centring limit. Good agreement between the analytical models and experimental results is demonstrated, with discussion of possible improvements. Overall, system damping behaviour is significantly improved by adding the extrusion based damping system.

1 INTRODUCTION

Earthquakes can cause significant damage and degradation, especially in beam/column connections. Current capacity design for monolithic reinforced concrete structures provides ductility by localising inelastic behaviour to specific regions called plastic hinge zones. Although plastic hinge damage provides significant energy dissipation during the event and provides adequate life safety, it is desirable to achieve these objectives without permanent structural damage. The use of rocking connections and, in particular, joints designed using the emerging Damage Avoidance Design (DAD) philosophy (Li 2006, Solberg 2007), enables the structure to undergo inelastic hysteretic response without any notable structural damage. This new design philosophy enables structures to be constructed that not only protect life safety, but also address the large financial cost of earthquake damage.

Jointed precast concrete systems conforming to this Damage Avoidance Design philosophy typically have low inherent damping and are particularly suited for supplemental damping systems. Recently, there has been considerable attention given to the use of yielding steel fuse-bars to provide hysteretic energy dissipation and modify the overall joint hysteresis (Li, 2006; Solberg 2007). Concomitantly, research into extrusion-based damping devices has resulted in the development of high force-to-volume lead extrusion dampers (Rodgers et al 2006a,b). These dampers provide force levels equivalent to, or much greater than, that provided by yielding steel fuse bars, and are sufficiently compact to allow placement directly into structural connections. This research outlines the experimental testing and analytical modelling of a prototype jointed precast beam-to-column subassemblage detailed according to the Damage Avoidance Design philosophy. As such systems perform in a bilinear elastic fashion without suffering damage, ideally supplemental damping should be added to improve energy dissipation. The present specimen was thus fitted with high force-to-volume lead extrusion dampers as a means of providing supplemental energy dissipation.

The primary focus of this paper is the effect of the lead extrusion dampers on the overall joint hysteresis. Analytical modelling of the experimental results is approached using a compound rate-dependent version of the Menegotto-Pinto rule. The development of an experimentally validated model will enable easy consistent design for applications in conjunction with spectral analysis-based design rules (Rodgers et al 2007).

2 EXPERIMENTAL INVESTIGATION

The prototype structure is a ten-storey reinforced concrete frame building with three 10m bays in each direction. This generic structure is commonly known as the “red book” building (Bull and Brunsdon, 1998), and was designed according to the New Zealand concrete standard (NZS:3101, 1995) for intermediate soil (NZS4203, 1992) in Christchurch, New Zealand. Keeping all other variables constant, the same structure was designed and detailed according to damage avoidance principles, thereby resulting in precast beams and columns being connected via a post-tensioning system. The DAD building was designed with precast flooring units running in the transverse direction and seated on the transverse beams, leaving the longitudinal beams to resist predominately seismic forces.

An exterior joint on the second floor of the prototype structure was chosen for testing of a 3D beam-column sub-assemblage. The joints were designed for a standard moment capacity of 500 kN-m. Using constant stress and strain similitude, the specimen was scaled to 80 percent of full size, and consisted of two beams in the longitudinal direction, and one beam in the transverse direction. The longitudinal and transverse beams are dominated by seismic and gravity loads respectively and are referred to as the east-west seismic and north-south gravity beams. A photograph of the experimental setup is shown in Figure 1 with experimental setup and instrumentation schematics. An initial 400kN axial post-tensioned prestress was provided by two 26.5mm diameter high-strength thread-bars placed in 50mm PVC ducts.

a) b)

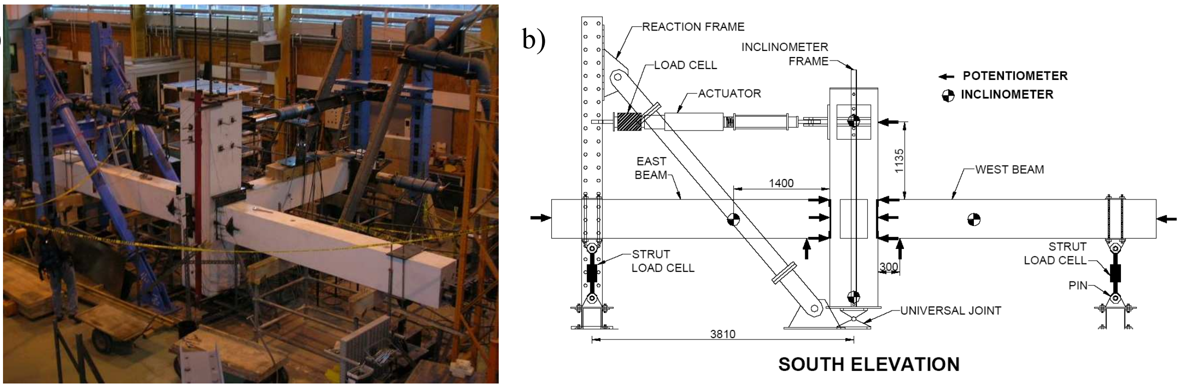

Figure 1: a) Photograph of the experimental test specimen, and b) Schematic south elevation showing test set-up and instrumentation (Solberg 2007)

The tendon profile in the east-west direction utilised a straight coupler system where the tendons were pre-bent at the joint end to a radius of 1.8m. The tendons exit through the column face at the top of the beam-column interface. Straight fuse bolt-bars run at an angle through the column, with a sacrificial fuse diameter machined to 75% of the effective area to localise inelastic tendon behaviour. A detailed schematic of the tendon and fuse-bar details for this east-west direction is presented in Figure 2.

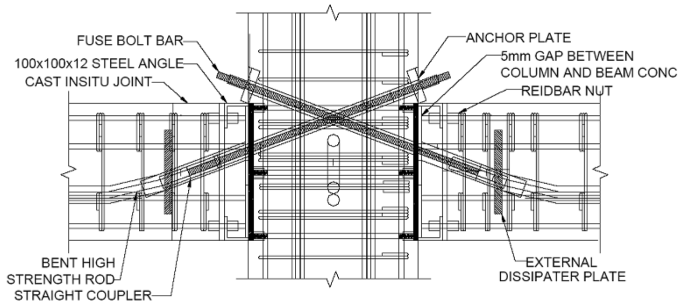

Figure 2: Post-tensioning detail at the beam-column joint in the East-West seismic direction. (Solberg, 2007)

The supplemental damping system consisted of two 120kN lead-extrusion dampers, one mounted externally to each seismic beam at out-rigger plates, as shown in Figure 3a. Figure 3b shows the hysteresis loop for the lead extrusion damper shown in Figure 3a. Only uni-direction testing in the east-west seismic direction is considered to evaluate the impact of these devices. Further construction and experimental details can be found in Solberg (2007).

a) b)

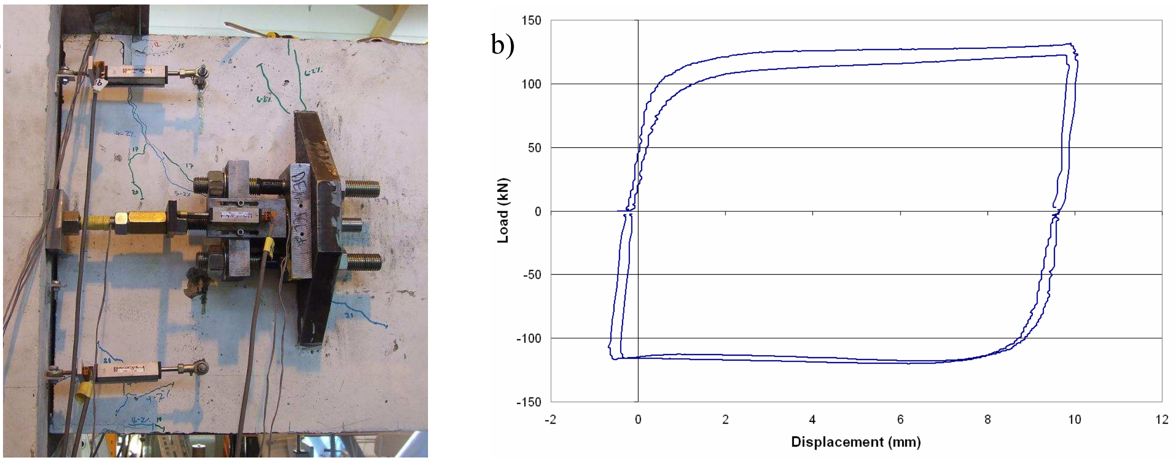

Figure 3: a) Lead extrusion damper externally mounted to the seismic beam, and b) hysteresis loop for the damper shown in a).

3 ANALYTICAL MODELLING OF JOINT BEHAVIOUR.

The overall joint hysteresis, in particular the column base-shear vs lateral deflection curve, can be modelled as a combination of elastic member deflection and rigid body rotation. Initially, the presence of post-tensioning will delay gap opening and lateral column deflection will be a function of elastic deformation of the prestressed concrete elements only. This elastic deformation regime continues until the applied moment created by the lateral loading of the column exceeds the moment preventing gap opening, as provided by the post-tensioned tendons and supplemental damping system. The column base-shear required for gap opening is therefore a function of the level of prestress provided by the tendons, and the resistive force provided by the dampers.

Upon gap opening, the prestressing tendons elongate elastically along with deformation of the supplemental damping system. Further lateral deflection is then a combination of further elastic deformation of the sub-assembly, and rigid body rotation associated with joint opening. The column base-shear associated with this deflection can be calculated using beam bending theory and rigid body mechanics. The post gap-opening stiffness continues until the tendon elongation associated with the rigid body component reaches tendon yield. At this point, further column deflection, and consequently column drift, occurs with no further increase in column base-shear.

The lead extrusion dampers are modelled as non-linear velocity dependent viscous dampers. The stiffness of the rods connecting the dampers to the column is assumed to be rigid, such that any damper deformation due to joint opening occurs only in the damper itself. Therefore, the dampers are assumed to take effect at the initiation of joint opening.

The combination of pre gap-opening elastic member deformation, post gap-opening deformation resulting in elastic tendon elongation, and post gap-opening deformation with inelastic tendon elongation creates an overall tri-linear hysteretic response. However, the smooth non-linear experimental behaviour can be more accurately modelled using a compound, rate dependent version of the Menegotto-Pinto (1973) Hysteresis rule, defined (Li, 2006):

$$F = \frac{(K_2 - K_1)\theta}{\left(1 + \left|\frac{K_1\theta}{F_p + F_D \operatorname{sgn}(\dot{x})}\right|^{\beta}\right)^{\frac{1}{\beta}}} + \frac{K_2\theta}{\left(1 + \left|\frac{K_2\theta}{F_y + F_D \operatorname{sgn}(\dot{x}) - (F_p + F_D \operatorname{sgn}(\dot{x}))(1 - K_2 / K_1)}\right|^{\gamma}\right)^{\frac{1}{\gamma}}} \quad (1)$$

where K_1 = stiffness of the sub-assembly during initial pre-gap-opening elastic deformation; K_2 = stiffness of the sub-assembly during post gap-opening deflection before tendon yield; θ = the drift angle of the column, $\dot{x}$ = the velocity of the damper shaft, corresponding to the velocity of the joint opening at beam centreline; where when $\dot{x} > 0$, sgn($\dot{x}$) = 1, and when $\dot{x} < 0$, sgn($\dot{x}$) = -1; F_p = column base-shear required to overcome the resistance to joint opening from prestress alone; F_y = column base-shear required to open gap to prestress tendon yield; β = exponent governing the degree of curvature that joins the tangents between the first and second linear sections of the hysteresis loops; and γ = exponent governing the degree of curvature between the second and third linear sections of the hysteresis loop, where large exponents give sharper corners closer to the tri-linear behaviour. Finally, F_D = column base shear required to overcome the lateral resistance of the subassembly due to the damper force, F_{damper}, defined (Rodgers, 2006a; Pekcan 199):

$$F_{damper} = C_{\alpha} |\dot{x}|^{\alpha} \operatorname{sgn}(\dot{x}) \quad (2)$$

where C_{α} = damper constant determined by testing at a reference velocity before installation into the joint; $\dot{x}$ = the velocity of the damper shaft; α = velocity co-efficient (constant), having a value of 0.12 (Rodgers et al, 2006a); and sgn($\dot{x}$) is as defined previously.

The initial system stiffness K_1 can be derived using moment-area theorems (Li, 2006):

$$K_1 = \frac{12(EI^*_{beam}) / L_b^3}{\left(\frac{L_{col}}{L}\right)^2 + \left(\frac{L_{col} - D}{L_b}\right)^3 \left(\frac{EI^*_{beam}}{EI^*_{col}}\right)} \quad (3)$$

where EI^*_{beam} and EI^*_{col} are the effective beam and column rigidities; L_b = length of the precast beams; L = clear length between column centerlines; L_{col} = column height; and D = beam depth.

Following gap opening, the second stiffness K_2 is defined (Li, 2006):

$$K_2 = \left(\frac{L}{L_b}\right)^2 \left(\frac{D}{L_{col}}\right)^2 \frac{K_{bolt} K_{ps}}{K_{bolt} + K_{ps}} \quad (4)$$

where $K_{bolt} = A_{bolt}E_{ps}/l_{bolt}$ is the stiffness of the bolt (fuse) bar, where A_{bolt} = area and l_{bolt} = length of the fuse portion of the bolt bar. Similarly, in Equation (4), $K_{ps} = A_{ps}E_{ps}/l_{ps}$ is the stiffness of the prestressing tendon in the precast beam, where E_{ps} = Young's modulus; A_{ps} = cross-sectional area, and l_{ps} = length of the prestressing tendon in the beam.

The lateral load resistance of the subassembly with both prestressing and energy dissipaters can be evaluated by considering rigid body kinematics. Assuming the neutral axis depth is small enough to be neglected and the horizontal force component from the threaded bolt bars is equal to the prestressing force in the bolt bars, joint equilibrium gives (Li, 2006):

$$F_p = \left(P^-_{ps}\frac{e}{D} + P^+_{ps}\left(1 - \frac{e}{D}\right)\right)\cos\alpha \frac{D}{L_{col}}\frac{L}{L_b} \quad (5)$$

where P^-_{ps} and P^+_{ps} are the total tendon force in the precast beam when rocking along the bottom and top edges respectively; e = eccentricity of prestressing tendon at column face, α = angle of the threaded fuse-bolt bars; and D, L, and L_b are defined previously.

Similarly, when considering the influence of the lead extrusion damper on the subassembly:

$$F_D = F_{damper} \frac{D}{L_{col}} \frac{L}{L_b} \tag{6}$$

where F_{damper} is defined in Equation (2).

Finally, the lateral strength at yielding of the sub-assembly is given by (Li, 2006):

$$F_{p\ yield} = P_{ps\ yield} \cos\alpha \frac{D}{L_{col}} \frac{L}{L_b} \tag{7}$$

where $P_{ps\ yield}$ = yield strength of fuse bolt bars.

4 UNI-DIRECTIONAL TEST RESULTS AND DISCUSSION

4.1 Exterior Joint Results

The experimental specimen was subjected to uni-directional displacement-controlled tests representing fully reversed sine wave profiles. These displacement profiles comprised drifts of 0.25, 0.5, 1 and 2%, where the specimen underwent two fully reversed cycles at each drift level. At 0.25% drift, the joint remained closed, with column deflection being a function of elastic deformation only. Minimal joint opening was observed at the 0.5% drift cycles, and notable joint opening was achieved at the 1 and 2% cycles. Movement of the column base pin due to flexibility in the connection to the strong floor resulted in some apparent hysteresis near the origin of the hysteresis loops. This effect was deemed to be due to this flexibility and does not represent a contribution to the overall joint hysteresis.

The hysteresis loops from the experimental specimen when subjected to cycles of 1 and 2% drift are presented in Figure 4. Figure 4 also shows the theoretical result predicted by the compound, rate dependent Menegotto-Pinto equation defined in Equation (1). The model shows good agreement with the experimental results.

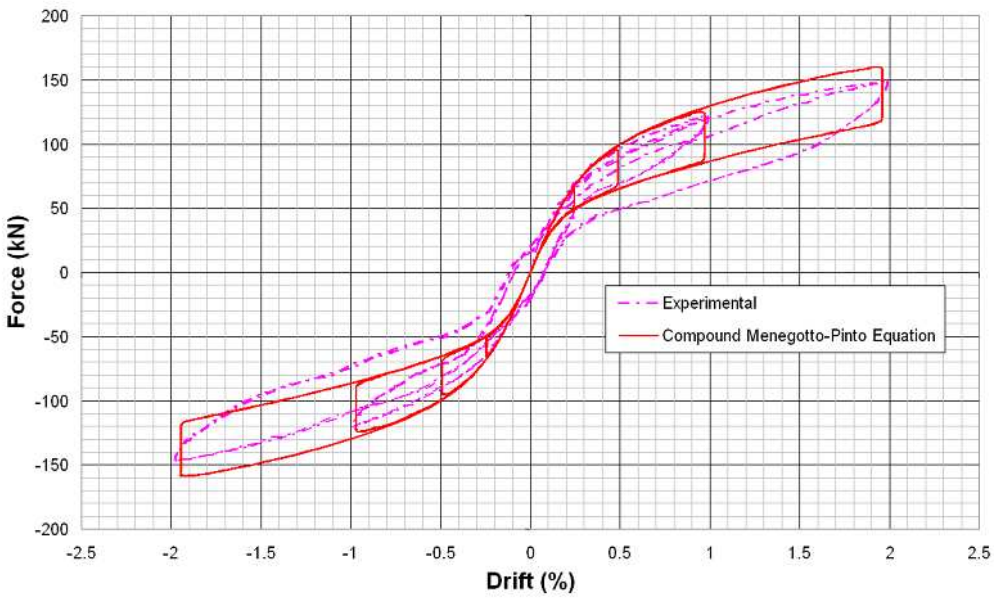

Figure 4: Experimental and analytical model results for prototype joint subjected to cycles at 1 and 2% drift.

The key differences observed in Figure 4 are a slight over-prediction in force from the Menegotto-Pinto equation, and that the loops from the theoretical model also show an over-prediction in the magnitude of the change in force that occurs at the peak drift points. Better agreement could be obtained by modifying the model to account for losses in tendon prestress due to the effects of friction. Adding a spring in series with the damper to account for flexibility in the damper mounts and connecting rods would provide better agreement at the extremes of the loop.

The primary focus of this paper is on the contribution of the damping system and associated modelling, so only the uni-directional test results are presented within this paper. Full bi-directional joint characterisation details are found in Li (2006) and Solberg (2007).

4.2 **Corner Joint Results**

The design force of 120kN for the lead extrusion dampers was a conservative choice from a design standpoint. The key motivation was to maintain a large factor of safety against the loss of overall joint recentring. If the resistive force provided by the dampers exceeds the prestress force then the joint could be at risk of no longer having the ability to self-centre following an earthquake.

After performing numerous tests on the initial test specimen, the east beam was removed from the test set-up, and both of the dampers placed on the west beam to double the damping force. This new set-up represents a corner joint for the building, and undertaking testing with this set-up allows the recentring limit to be experimentally investigated. It is important to note that a breach of the recentring limit represents the requirement of an external force to recentre the joint, and is shown in a hysteresis loop by a zero-force crossing of the horizontal axis at a non-zero displacement value.

Furthermore, it was of particular interest in this comparison to investigate the contribution that the supplemental damping system contributed to the overall joint hysteresis. Therefore, testing was performed on the joint with and without the dampers attached to indicate the hysteresis loops that are obtained for these two configurations. Testing was again limited to uni-directional displacement inputs for these configurations as no damping system was applied to the north-south gravity beam, rendering it unimportant here. The peak drift for the displacement inputs was increased to 4%, but two fully reversed cycles at each drift increment are used to investigate repeatability and the effect of any inelastic tendon behaviour. Results for 1, 2, 3, and 4% drifts, with and without dampers are presented in Figure 5.

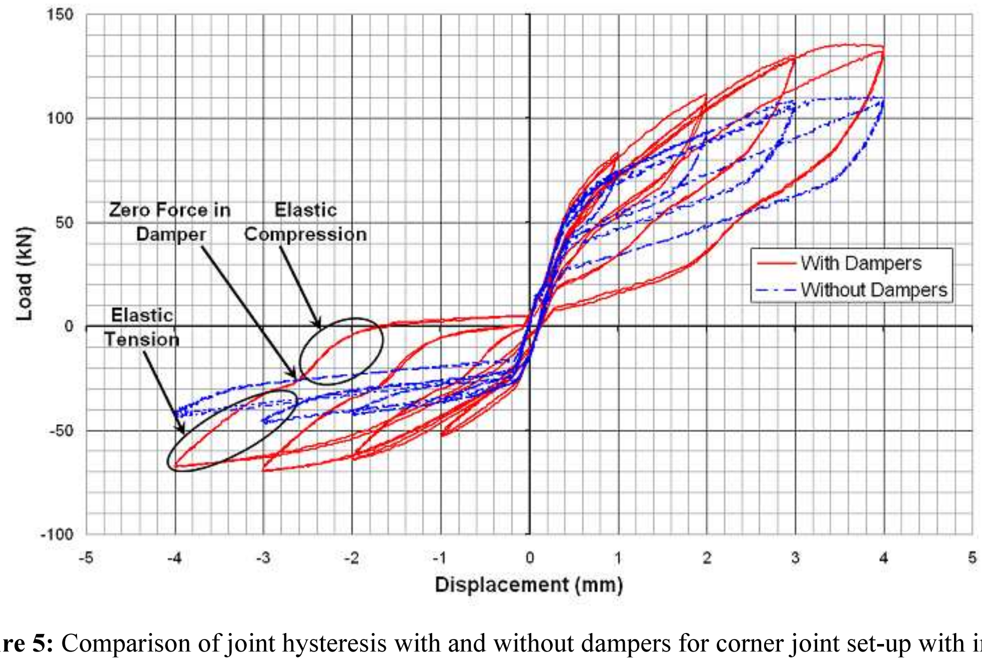

Figure 5: Comparison of joint hysteresis with and without dampers for corner joint set-up with increased damping for loading at 1, 2, 3, and 4% drift.

The first notable observation is that the hysteresis loop is asymmetrical. This phenomenon can be attributed to the fact that the post-tensioning tendon arrangement of the prototype has the tendons eccentrically placed relative to the beam centreline at the beam-column interface, as shown in Figure 2. Although this eccentricity has always been present, the loops presented in Figure 4 do not show this asymmetry as the presence of both the east and west beams balanced out this effect. Although the forces at each interface were asymmetrical, the west interface was undergoing the opposite joint rotation to the east interface, resulting in overall symmetry of the hysteresis loops. The removal of the east beam removed this cancellation, resulting in the asymmetry seen in Figure 5.

It is also apparent that the hysteresis loops are substantially larger for the joint when the dampers are present. This result is expected, as the primary purpose of the dampers is to provide increased energy dissipation. Interestingly, the area enclosed within the hysteresis loops for the joint without dampers shows large disparity between the two directions. Again, this phenomenon can be traced back to the tendon profile. The inherent hysteresis for the joint without dampers is related primarily to the friction between the prestressing tendons and the PVC tube in which they are contained. The bent tendon arrangement results in notable friction between the tendon and PVC duct as the tendon undergoes deformation from gap opening. The curve of the tendon naturally results in higher friction for gap-opening in one direction than the other.

Another important observation is the loss of recentring ability for the joint at 4% drift, as seen by the crossing of the horizontal axis at a non-zero displacement. Although the recentring capability is lost, it is only lost for negative drift angles at the largest drift of 4%, and the external force required to recentre the joint was only 5 kN. This result indicates that the use of this level of damping would be slightly beyond the upper limit that should be incorporated in design if large drifts are expected.

Finally, Figure 5 indicates that the effect of connecting rod and damper mount flexibility has a notable effect on the overall hysteretic response. At peak drift, the connecting rods to the dampers are in a state of elastic tension due to the load they are carrying. Immediately after peak drift the connecting rods must undergo a period of reduction in elastic tension before then undergoing elastic compression before the damper can provide energy dissipation. The effects of this flexibility can be clearly seen in Figure 5, where as well as this elastic deformation, there is an inflection point where some “slip-slop” can be observed in the damper mounts. These factors all slightly reduce the effectiveness of the dampers, and designers are advised to use as stiff as practicable connecting rods and mounting plates.

Lead extrusion dampers have several key benefits when compared to the use of yielding steel dissipaters. The controlled deformation within the damper enables elastic design of all connecting rods, eliminating the potential of low-cycle fatigue that is present with yielding steel. Secondly, lead extrusion dampers can provide consistent force on repeated cycles, and do not suffer the buckling issues that are present with yielding steel. These advantages result in more consistent and repeatable joint behaviour and the dampers will not need to be replaced following a large earthquake.

5 CONCLUSIONS

The use of a compound, rate dependent version of the Menegotto-Pinto hysteresis rule provides a compact and satisfactory method of modelling joint performance. When compared to the experiments the model slightly over-predicts the column base-shear during drift cycles, but this effect could be addressed by allowing for prestress loss due to friction in the ducts. The area enclosed within the loops is slightly over-predicted as the model does not allow for elastic deformation of the connecting rods and any deformation or slip in damper mounts. These latter factors slightly reduce damper efficiency. Note that the effect of the flexibility will always be present to an extent, but can be incorporated into the model by adding a spring in series with the damper.

Testing of a corner joint, with only one seismic beam revealed the presence of response asymmetry, both in the magnitudes of the column base-shear during deformation, and in the amount of inherent damping within the joint. These factors relate to the bent tendon profile, and were cancelled in the presence of an opposing beam. The use of lead extrusion dampers in place of yielding steel dissipaters provides more repeatable joint behaviour and eliminates low-cycle fatigue issues. In general, improved hysteretic performance for jointed beam-to-column connections using lead extrusion dampers has been successfully demonstrated. The overall outcome complies with the general tenets of Damage Avoidance Design.

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