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High force-to-volume extrusion dampers and shock absorbers for civil infrastructure

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ABSTRACT: The ability to dissipate structural energy from seismic, wind and impact loads in a controlled and repeatable manner is essential to maintaining structural integrity for a range of large environmental loads. Extrusion based damping technology is a promising method of achieving these design requirements and is already widely used in base isolation applications. However, the large size of current devices prevents several unique implementations limiting their widespread use. This research develops high force-to-volume extrusion dampers small enough in volume for use in typical structural connections. Re-centering extrusion-based devices extend the technology to high impact loading applications. Design, analysis and experimental verification has been undertaken on lead extrusion dampers sufficiently compact to allow direct placement into universal column sections nominally 350mm deep (W14). Peak force levels up to 450kN with strokes up to 50mm are developed with an optimal (almost fully rectangular) hysteresis loop. Shock absorbers for high force impact loading applications with some recentering capability are developed, with stiffness values up to 3.6 MN/m, and force levels up to 300-400kN. These latter devices have significant potential for industrial structural impact loading applications, such as moorings of large ships. The overall results indicate that maximum energy dissipation with high force/volume relationships can be developed and characterized for lead extrusion dampers.

1 INTRODUCTION

Earthquakes, large wind and impact loads can cause significant structural damage, particularly at beam-column connections where the formation of plastic hinges results in a degradation of structural integrity. The associated damage provides significant energy dissipation during the event, but can be difficult and expensive to repair. It is therefore desirable to develop a means to achieve this energy dissipation without structural damage.

The development of active and semi-active structural technologies has received significant research attention in recent times, and has been shown to produce significant reductions in seismic response (Chase et al, 2006; Barroso et al, 2003; Housner et al. 1997). These systems have several drawbacks when compared to a passive system. Although semi-active systems do not require the large power sources of fully active systems, they still involve complexity in sensing response and implementing the desired control law. A passive system does not require any of these sensing, computing or actuation mechanisms and can thus be relatively inexpensive to manufacture and implement.

Moreover, passive control systems may also require little significant regular maintenance. Passive systems developed and currently used for energy absorption and base-isolation applications include lead extrusion dampers (Cousins & Porritt, 1993) and lead-rubber bearings (Robinson 1982, Robinson 1995). Hence, they are a well developed structural technology that is accepted in the structural design community.

Lead extrusion dampers used in previous structural applications have been quite large due to the relatively low internal pressures. Their large size is often considered an impediment, preventing implementation into several possible applications. Therefore, a compact, high internal pressure damper would enable significant potential new structural applications, particularly in extending applications to implant dampers within structural connections.

Hence, such a damper must be significantly smaller than existing extrusion dampers to broaden possible structure placement into situations with tight volume constraints. However, they must still provide the force capacity and energy dissipation of existing, much larger, dampers. More specifically, a high force to volume extrusion damper, relative to existing devices, is required to broaden the application of this from of technology.

New applications enabled would include bridge piers and structural connections, and these devices are also particularly well suited to connections that utilise jointed Damage Avoidance Design connections, as such joints have low inherent structural damping. Placement into structural connections is possible for both reinforced concrete and steel frame buildings, and the non-linear velocity dependent elasto-plastic hysteretic behaviour provides an almost ideal hysteresis loop, enclosing the maximum area within the force and displacement constraints. Previous research has shown that these devices can produce significant reduction in seismic response based on spectral response analysis over suites of probabilistically scaled ground motions (Rodgers et al, 2006).

This research outlines the experimental testing and development of high force-to-volume dampers. The preliminary design analysis and some experimental verification of re-centering structural shock absorbers presented further extends possible applications of these devices to reduce impact loading forces and provide re-centering capability to rocking joints that utilise the Damage Avoidance Design. Unique device design is also shown to enable non-symmetric hysteresis loops that maximise energy absorption, but minimise residual drift.

The goal of this research is to provide an experimental investigation into the efficacy and implementation of high force-to-volume extrusion dampers. It also presents possible future developments made possible by elegant device design with recentering capability. In this context, the design space for advanced recentering devices using these same principles are also presented.

2 DESIGN AND ANALYSIS

2.1 *Experimental Device Development*

Lead extrusion dampers can be categorised into two groups based upon fundamental design differences. These groups are the constricted tube type, and the bulged shaft type (Cousins & Porritt, 1993). Both types utilise the same basic concept of providing a resistive force by plastically extruding lead through an orifice created by an annular restriction. For a constricted tube damper, the orifice is created by a constriction on the bore of the outer cylinder. In contrast, bulged shaft dampers utilise a streamlined bulge on the central shaft. The relative merits of each are documented (Cousins & Porritt, 1993) and focus primarily upon ease of manufacture and the ability to achieve predictable and repeatable performance.

The prototypes constructed and tested within this research are based upon the bulged shaft design for low cost and ease of manufacture. The design of the initial prototype is presented with basic dimensions in Figure 1. A second prototype device was also constructed and tested, with a similar design to that shown in Figure 1, but with an internal cylinder diameter of 66mm, and a wall thickness of 20mm.

The plastic deformation associated with the extrusion process absorbs large amounts of energy and provides a much stiffer damper capable of absorbing far more energy than an equivalent sized fluid viscous damper due to the much larger bulk modulus of the lead. Two major factors limit the amount of energy that can be dissipated. First, the shaft yield load, based on size and material, restricts force levels. Second, the heat produced by the damper on repeated cycles softens the surrounding lead and reduces resistance. Both factors can be reasonably managed by the device design and manufacture.

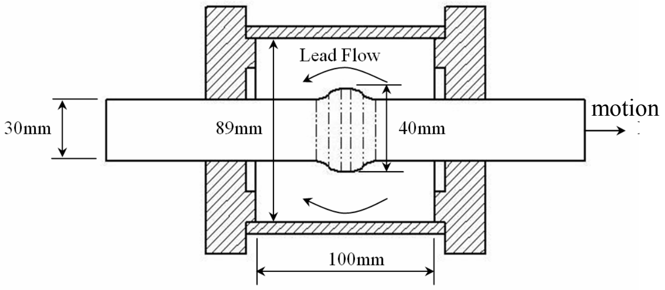

Figure 1: Cross-sectional view of the initial prototype design with damper dimensions

One major issue with this method of damping is the formation of voids within the working material as it is extruded through the restriction. For a lead extrusion damper, this void formation is due to the lead compressing, expansion of the cylinder wall, and imperfections in the casting that leaves air gaps or micro-sized voids that can be compressed. Hence, as the bulge moves through the material it is compressed into a smaller volume, leaving a trailing void. Thus, as the bulge passes through this void on following cycles the damper experiences less resistance and dissipates much less energy. To minimize void formation in this study the lead is prestressed, which helps reduce casting porosity and air gaps before the damper is used. Thus, the size of the void, as a percentage of the total lead volume, is minimised to optimise performance of the final device design.

2.2 *Device Design*

The damper is designed to fit into confined spaces within and around structural connections, such as the applications presented in Figure 2. Figure 2a shows a damper set up to reduce lateral motion and absorb the response energy of a bridge deck and framing. In this application, simulations have shown that a damper rated around 10% of the weight of the structure can reduce spectral structural accelerations and displacements by over 50% (Rodgers et al, 2006). The dampers could also be arranged longitudinally and anchored into bridge abutments, if needed.

Figure 2b shows a steel connection application with tight space constraints. Here, the damper must fit between the flanges of universal column sections nominally 350mm deep (W14 using American steel sections) to broaden possible application into high rise structures. As the joint rotates the clearance allows movement, transmitting the building motion to the damper, instead of the yielding the structural steel elements. The shaft has been limited to 30mm diameter, in keeping with maximum fitting sizes commonly used in structural applications. The limiting factor in the design is the 30mm, high strength steel shaft with a yield force of approximately 500kN, which is greater than the desired 250-400kN peak fore levels.

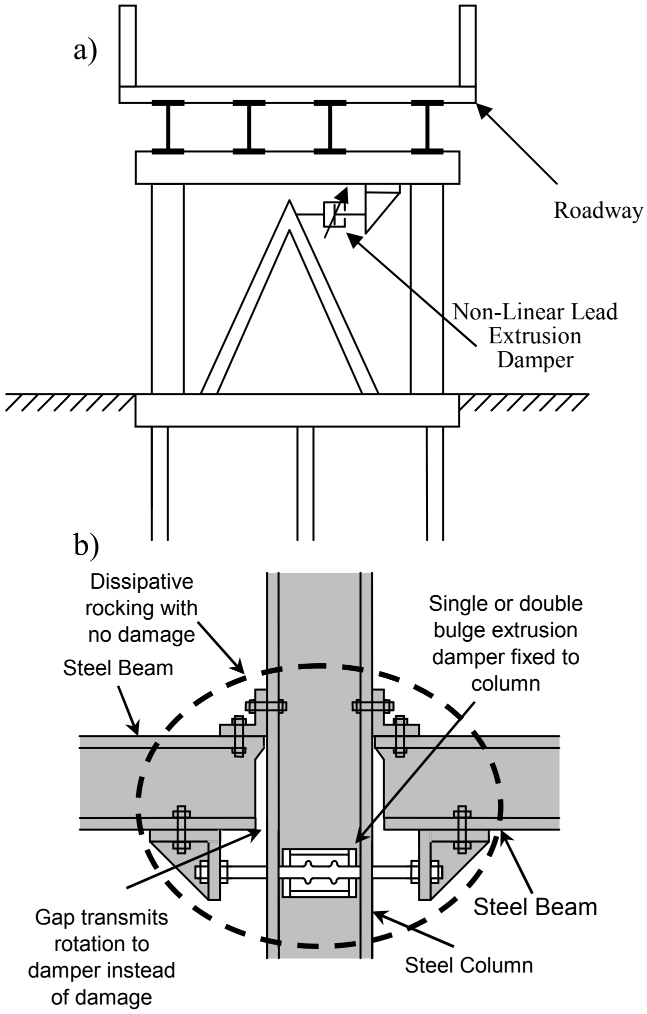

Figure 2: Possible placement of dampers into structural connections – a) a bridge pier, and b) a steel joint

2.3 *Experimental Methods*

Quasi-static compression tests were undertaken on the initial design shown in Figure 1, to characterise the force-displacement behaviour. Speed variations are used to identify the velocity exponent which governs the increased forces seen as energy is dissipated more rapidly via faster extrusion. The velocity exponent can thus be used to estimate the force in full speed testing from quasi-static test results. This force-velocity relationship is defined (Pekcan, Mander, & Chen, 1999):

$$F = C_{\alpha}\dot{x}^{\alpha} \tag{1}$$

where F = the extrusion damper force, $\dot{x}$ = velocity of the shaft, α = velocity coefficient (constant), and C_{α} = device constant determined empirically.

Testing was performed on a range of different prototypes comprising different bulge diameters, internal cylinder diameters, and cylinder wall thickness. This range of experimental results enables empirical device relationships to be created to estimate force levels for future device design. Most of the prototype devices were tested with and without the presence of a prestress in the lead to investigate void formation and the effect of prestress on the resulting hysteresis loop and device performance.

3 RESULTS AND DISCUSSION

3.1 *Results without prestress*

Initial manufacturing methods used as-cast lead as the working material. When the lead solidified, shrinkage occurred along with the development of small micro-voids due to trapped air. Hence, the lead did not completely fill the volume inside the damper, and these extra volumes can be compressed and contribute to creating a trailing void behind the bulge.

The hysteresis loop for a 40mm diameter bulge and no prestress, presented in Figure 3, shows the first stroke produced a peak force of 90kN, reasonably constant throughout the stroke and in line with design expectations. During the return stroke the force was significantly lower at around 50kN until "new" material was entered at the device midpoint. After the initial stoke in each direction the force was effectively constant around 50kN.

The cause of this drop in force is the coring out of the lead as the piston was forced through. Hence, the lead was compressed, rather than flowing around the piston as desired. The inside of the cylindrical trailing void had a measured diameter of 38mm, indicating that the lead was only flowing back about 1mm around each side. Effectively, the lead compressed enough so that approximately 8-10% of its volume was lost. With the 40mm bulge this loss made a relatively constant void along the entire 30mm diameter shaft of 38mm diameter, resulting in the lower force levels seen in Figure 3.

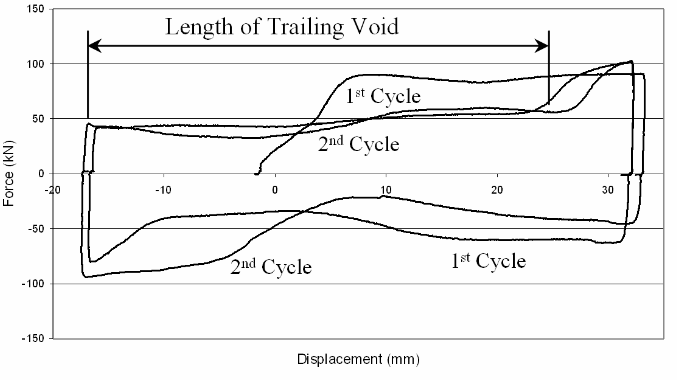

Figure 3: Hysteresis loop for 40mm diameter bulge on 30mm diameter shaft without prestress

The hysteresis loop for the 50mm bulge without prestress shows the same characteristics as the 40mm case in Figure 3, but with reduced coring effects. Because of the increase in diameter of the bulge the same 8-10% volume air void, has a reduced length, as is seen in Figure 4. These results thus show a more optimal ‘square’ loop than the 40mm case. The shape of the loop shows the air void created behind the bulge to be only approximately 10mm, which is an improved result. The peak force produced was between 220kN and 230kN, and thus closer to expected values for much of the stroke.

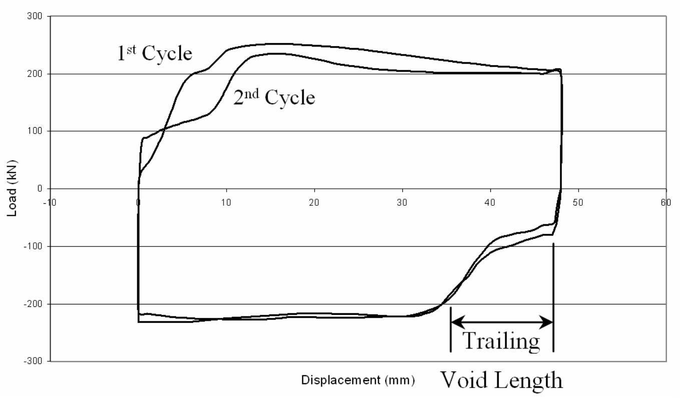

Figure 4: Hysteresis loop for 50mm diameter bulge on 30mm diameter shaft

Strain gauges mounted on the 6.5mm thick cylinder wall of the device shown in Figure 1 revealed plastic deformation of up to 2% as the bulge passed. This deformation would also contribute to the formation of the trailing void as perfect confinement of the working material was not maintained. Reducing the void is important to increase energy dissipation by maximizing time at peak force. To reduce the trailing void and minimise the amount of compression of the lead the same devices were tested after first prestressing the as-cast lead.

3.2 *Results with prestress*

After the as-cast lead solidified within the cylinder, a 400kN force was applied to compress any air voids in the casting and put a residual compressive stress on the material. Figures 5-6 show the hysteresis loops of the results from the initial prototype with 40mm and 50mm bulges after prestressing.

Figures 5-6 show much ‘squarer’, more optimal, hysteresis loops for both bulge sizes. The trailing void formation remains, but has been reduced dramatically. Figure 6 show that trailing voids are only approximately 2-3mm long for the larger 50mm bulge and 20mm for the 40mm bulge. However these voids are at least 3 times smaller in volume than without prestress, resulting in much smaller drops in force, more time at peak force, and consequently more energy absorption and dissipation.

Disassembly of prototype devices following testing has indicated that without the application of prestress the compression of the lead is approximately 8-10% of the total volume of lead. The application of prestress reduces the void volume by 3-5x, giving a volume equal to approximately 2-3% of total volume. The smaller void volume results in the much more desirable and repeatable hysteresis loops seen in Figure 6.

Equally important, is the rise in force produced by the dampers when the lead is prestressed. More specifically, there is an increase of 80kN for the 40mm bulge and 35kN for the 50mm bulge from the non-prestressed results for the initial prototype. This result is due to the reduction in casting porosity by the compression of the lead in the prestressing process, and greater constriction of the lead due to the residual compressive stress. However, as the larger bulge size also provides a greater constriction, this difference in force decreases as bulge size increases.

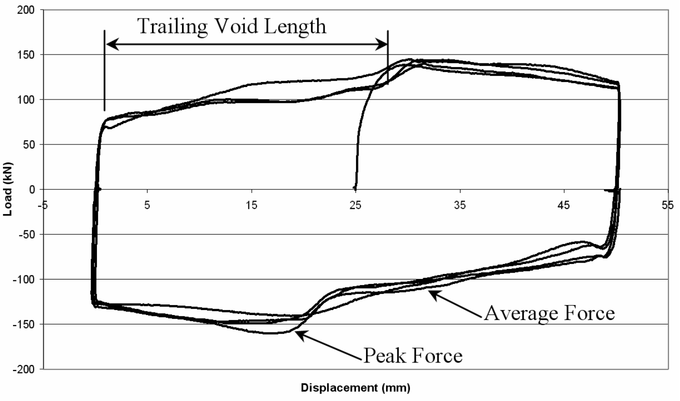

Figure 5: Hysteresis loop for 40mm diameter bulge in the initial prototype with prestress

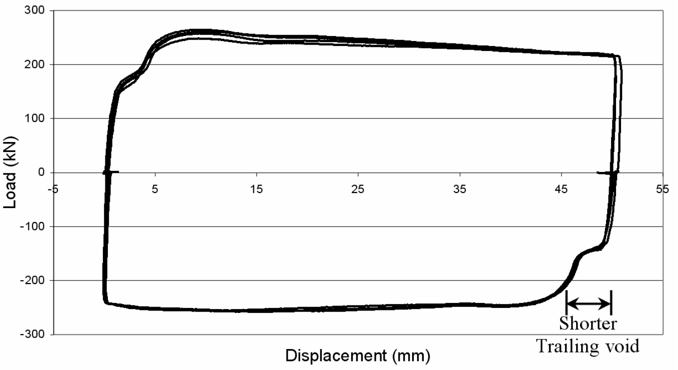

Figure 6: Hysteresis loop for 50mm diameter bulge in the initial prototype with prestress

Although there is still a force reduction over part of the stroke when the 40mm bulge is used, this effect appears unavoidable unless a very large prestress force is applied. In this case, the force reduction is also partly due to the relatively low height of the 40mm bulge over the 30mm shaft. Since the 40mm bulge has a small face area, a given trailing void volume will produce a noticeable reduction in force over a longer part of the stroke. This effect can be minimised using larger bulge sizes or a different manufacturing process.

The hysteresis loops in Figure 6 show almost no reduction in force due to void formation. There is a small ‘cut out’ in the hysteresis loop for the first 4mm of every stroke, but this small reduction is not large enough to have significant effect. The almost perfectly square shape means the device is absorbing the maximum amount of energy per cycle.

3.3 *Experimental Relationships*

The average peak forces from the test results were used to relate device parameters to force produced. Figure 7 shows the relationship of bulge diameter to force, and includes the estimated 40kN friction force and shaft yield strength at maximum bulge diameter for the initial prototype. Note that the fitted line is almost exactly linear and thus different from the relationship presented in Pearson et al (1960) for a similar extrusion process.

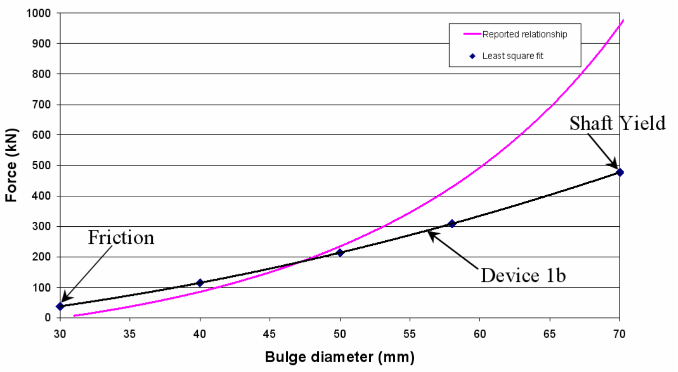

Figure 7: Experimental relationship showing experimental and reported extrusion relationship.

As an alternative to the extrusion theory presented, a more straightforward stress-based model was considered. Using the Mohr-Coulomb failure criteria for a quasi-brittle material, the resistive force for the device, D_D, is defined:

$$D_D = \tau_D A_{shaft} + \sigma_o A_{face} \tag{1}$$

where τ_D = shear stress due to the load between the shaft and the lead; A_{shaft} = surface area of the shaft; σ_o = direct stress imposed upon the bulge face area; and A_{face} = annular face area of the bulge. Least squares fitting of τ_D and σ_o to the experimental data yielded $\tau_D = 4.0$MPa and $\sigma_o = 140$MPa.

These results can be found from examining Mohr’s circle of stress for lead in the unconfined condition. First, the maximum shear stress is $\tau_D = \sigma_y/2$ where σ_y = unconfined yield stress of lead of 6-11MPa. Second, σ_o is well above the unconfined compression strength. However, due to the thin wall thickness of the cylinder in the initial prototype the confining stress can be restricted to a value corresponding to cylinder wall yield, $\sigma_C = 36$MPa. This result implies a confined lead strength relationship defined:

$$\sigma_{PbC} = \sigma_y + 3.6\sigma_C \tag{2}$$

The shear stress, τ_D, calculated, leads to a force for an un-bulged shaft of 37.7kN which is close to experimental estimates of the friction force from unprestressed experiments with 40mm bulge. However, more results are clearly needed to verify this new model of working material mechanics.

3.4 *Development of recentering devices*

In many structural applications it is desirable to have dampers with recentering capability, to assist in structural rencetering and minimising residual drifts. Theoretical investigation and design of dampers with non-symmetric hysteretic behaviour has indicated that these devices could have significant benefit for structural applications utilising Damage Avoidance Design.

These devices utilise a change in volume to provide a resistive force on the shaft, with a resulting force acting to return the shaft to the original position. Preliminary designs of devices with these characteristics are shown schematically in Figures 8 and 9. Both designs utilise the shaft displacement to cause a change in volume, and hence, provide a resistive force on the shaft.

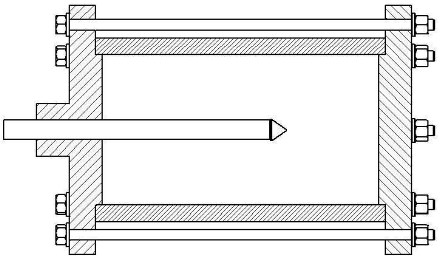

Figure 8: Preliminary recentering device design

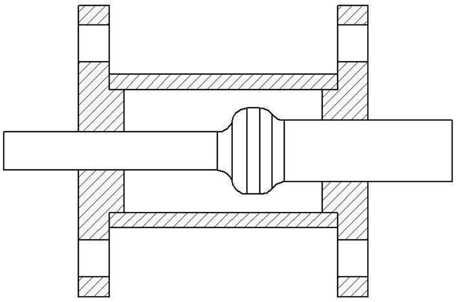

Figure 9: Possible extrusion based recentering device

Preliminary analysis has indicated that lead is too stiff to provide a design stiffness of 500-700kN/m that would suit several appplications. The analysis is based upon elastic deformation of the working material, and the high elastic modulus of lead prevents it being a viable option as the induced strain is impracticably low for the required design stiffness. More specifically, volume changes of 10-20% should be expected in operation for feasible design.

The construction of tradeoff curves can parameterise the design space and indicate a more suitable working material. Figure 10 shows where possible working materials lie for a 500-700kN/m device. For example, Bitumen is suggested as a possible working material as it has a lower elastic modulus of approximately 0.5GPa.

One possible application for these recentering devices is to apply prestress to rocking joints that utilise Damage Avoidance Design. The use of rencentering devices could replace the prestress tendons that are traditionally used. A schematic representation of such an application can be seen in Figure 11.

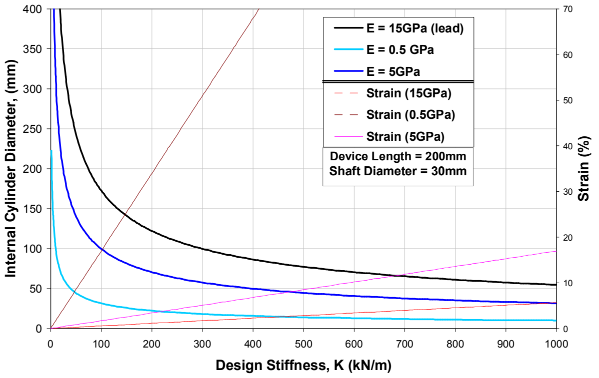

Figure 10: Tradeoff curves investigating possible working materials.

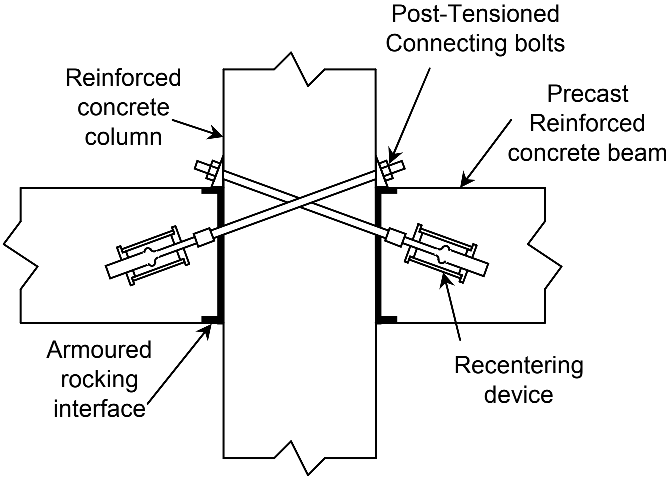

Figure 11: Schematic representation of recentering device placement into reinforced concrete connection using the Damage Avoidance Design details.

4 CONCLUSIONS

Compact 300-400kN dampers have been designed and experimentally validated. Prestressing the cast working material is critical as it removes porosity and provides a beneficial compressive residual stress. The result is that the hysteresis loop is more optimally 'square' and the resistive forces generated and energy dissipated increase. Detailed trade-off analysis is used to develop simple design curves for similar devices. From this result, a new model of the device process is also presented. Overall, the compact high force/volume dampers presented are an important initial step towards a wide variety of novel applications particularly in structural connections, and improved structural resilience.

Extension of this technology to obtain dampers with recentering capability shows further potential for structural applications, such as minimising residual drift. The design of such devices poses material selection issues, with the rheological and hysteretic behaviour of possible working materials requiring careful consideration.

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