Supplemental Damping for the seismic retrofit of 8-storey RC Hotel building in the Mexican Pacific using Yielding Restrained Braces – part A, Comparison of alternatives

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ABSTRACT

Seismic friction damper application for the seismic retrofit of a concrete building in a high seismic zone. The system is designed using a conventional force-based method and reduction factor. The Yielding Restrained Brace (YRB) concept is presented, relying on limiting the forces in braces by using Ten-Co seismic brake and evaluating long term stability (with respect to corrosion). The system is compared against two alternatives, concrete shear walls and Buckling restrained braces (BRBs), showing differences in final design and costs. In a separate document, **Part B,** the simplified linear method to design with YRB frames is explained and its effectiveness is then confirmed by a NLTH.

Keywords: seismic dampers, friction damper, seismic retrofit, Yielding Restrained Brace (YRB), linear design.

INTRODUCTION

A major hotel project was about to be conceived in the Mexican state of Nayarit. This project is located on the highest seismic zone of the Mexican pacific and is categorized as such for the local regulation. The project consisted of a series of more than ten buildings from which three were existing buildings in reinforced concrete built in 2000, before the latest update of the Mexican code [1]. In addition, these buildings presented some degree of observable deterioration in structural elements given exposure to the environment after their initial construction. Engineers in charge of the project also noticed that the structural configurations didn't strictly follow the exiting structural plans.

Existing structure and seismic demand

Existing buildings were numbered, buildings #3 & #5 are mirror images of one another and #4 being the central building. Results in this document refer to building 3 only for ease of reading, the reader can consider results for buildings 4 and 5 equivalent. The building had some unfinished areas, some of which had exposed structural elements and some with full finishing (see Image 1).

Image 1 *Buildings 4 and 3 in soil exploration. Courtesy of Soils Solutions S.A. de C.V.*

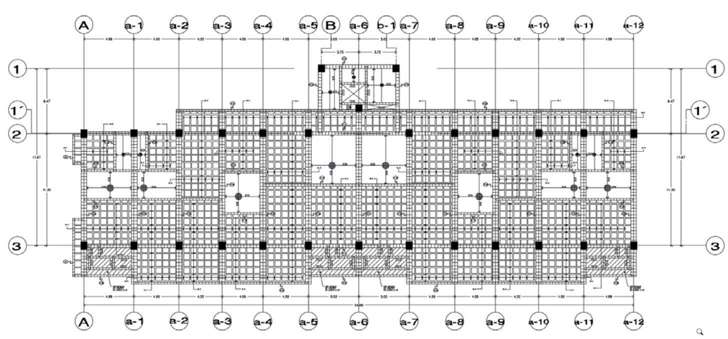

Image 2 *Existing structure, firs floor plan*

The existing moment resisting frame structure (see Image 2) was 21.7m height with inter storey height of 3.4m and 4.3 in the last floor. Notable was the finding that during construction too many perforations had been done to some beams and slabs. After carrying out material testing, they decided to limit concrete capacity to $200kg/cm^2$ and to consider the structure as moderately ductile. Existing foundation was formed by a single 100cm pile per column with 20m depth. With 15m width in the short sense, the structure was excessively flexible: expected spectral accelerations of 1.63g and a drift of approximately 0.03h, double the code allowance for such structures.

Alternatives

Engineers performed a preliminary assessment of several options. Base Isolation provides extra flexibility at the base, increasing period by around 1 to 1.5s. [2], However, the reductions in accelerations to approx. 0.4g still required important interventions on columns. Column capacity ratios in the first three storeys were still higher than 1, going up to 1.3. Since isolators already represented a costly alternative and were considered to avoid major works in the super structure: this option was quickly disqualified. Lead core isolators were not considered, as the building owner didn't want to have permanently deformed elements at the base of columns, that may require future inspections.

This led to either a combination of ductility and brute strength, or some kind of additional damping. Damage based dampers, such as TADAS or ADAS, were not considered due to uncertainty in the actual yielding point. Metallic yielding devices, would have too many factors affecting the yielding point, especially velocity and strain rate [3] [4], and for this particular seismic zone, engineers wanted more certainty. Although BRBs also have this problem, the fact the core is contained, gave the perception to the designers that it may reduce some of the risks. Viscous dampers were disqualified because 1-The structure requires significant additional stiffness in the short direction (Y), 2-Variations of velocity in the ground motions for the site added more complexity in the system calibration 3- Costs were prohibitive.

Three economically viable options that would replace the existing SFRS and/or offer supplemental damping were considered for further development:

- Brute strength with ductility using shear walls as the SFRS
- Dissipating seismic energy with the ductile capacity of Buckling Restrained Braced frames
- Dissipation with Yielding Restrained Braced frames

Brute strength with ductility using shear walls as the SFRS

In this option the existing SFRS would be fully replaced with shear walls of 35cm and 45cm thick in the long and short side respectively (see Image 3). Reduction factors of $R_d = 3$ and $R_o = 2$ accounting for ductility and overstrength of the new system were used. A whole new set of beam and columns was created to reinforce the existing ones and the entire existing slab reinforced with W type profile beams to ensure a rigid diaphragm. Despite the reduction factor used, foundations still required major strengthening due to the increased accelerations in this much stiffer alternative. A whole new set of footings of 1.75m deep and 7.8m x 6.3m surface were designed along with 35, 20m deep piles with diameters between 100 and 160cm (see Image 4).

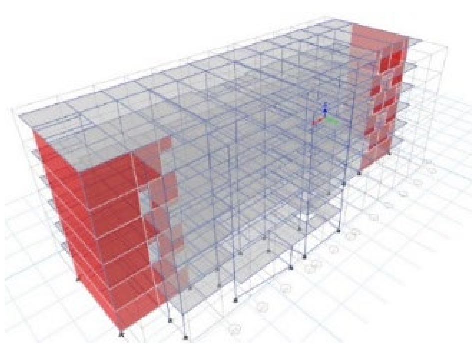

Image 3. Model with shear walls as SFRS

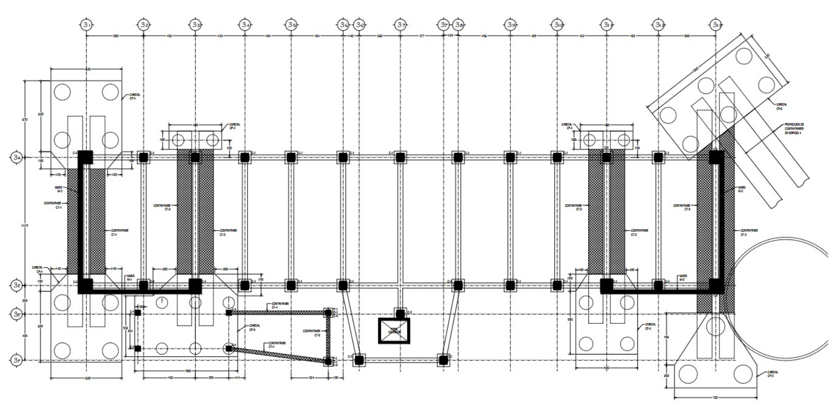

Image 4. Foundations design of the shear wall alternative, 36 piles

Even with this large-scale upgrade, the structure was still utilizing damage as the energy dissipation method. A "Moderate-code" mid-rise structure like this one, according to [5] can expect ultimate capacity around 0.417g and displacement in the roof of 13cm in average. This will imply ductile deformation of 0.0067h on average, representing moderate to extensive damage in this system. This was consistent with design acceleration spectra value of 0.37g used for this model as design parameter.

Dissipation with the ductile capacity of Buckling Restrained Braced (BRB) Frames

In this alternative the SFRS would be composed out the existing frames equipped with BRBs. Architecturally, only one frame could be used in the long side (X) for bracing, as the other side faced the beach and the owner didn't want to risk the view from the hotel rooms (see Image 6). For this model, engineers applied a total reduction factor of $R_d = 2$ and $R_o = 1.5$ because Mexican code [6] required to not use $R_d > 2$ for retrofits where the SFRS is not fully replaced. Design accelerations were around of 0.39g.

Non-factored drift limits for this alternative were 0.01h. With cores between 18 and 89cm^2 in the long side (X) and between 45 and 196cm^2 for the short (Y), the BRBs were not able to develop enough ductility in the lengths available in the long side (X). This meant that, at least in the X sense, the BRBs would not dissipate much and their failure may be abrupt. Furthermore, in the short side (Y) the overstrength problem remained an issue. Typically, a BRB will double or almost triple its initial yielding point before failure (see Image 5), which requires that such increases in forces be taken into account for foundation strengthening, which in this case were already weak. Foundation re-design for this option was similar to that of the shear wall alternative (see Image 4).

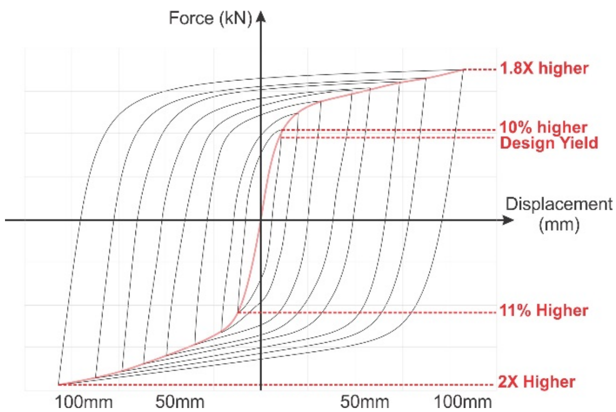

Image 5. Typical BRB hysteretic loop

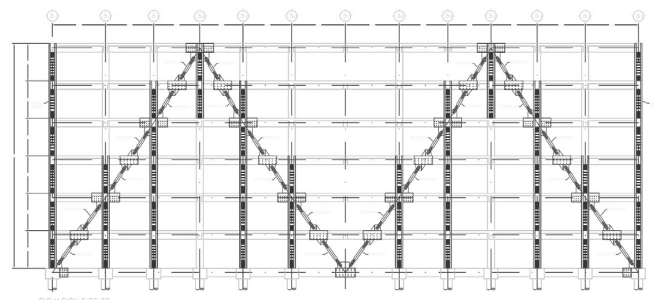

Image 6. BRB alternative in the long side (X) (left), short side (Y) right, columns jacketing

Finally, the fact that only one axis was available for bracing in the long sense (X) raised questions on the Out of Plane forces in the BRBs. This well know challenge [7], will require strong jacketing for torsion shear in the columns at the opposite side and (see Image 7), and certainly, real scale testing of the full assembly as required per standards [8] to establish real failure mechanism. This would make this alternative cost prohibitive.

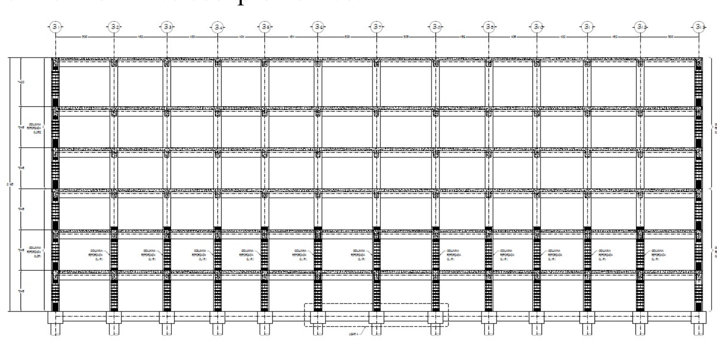

Image 7. Opposite side long (X) columns jacketing

For these reasons, the engineers decided not to proceed further with the alternative. The initial cost benefits of using a damage-based technology like BRBs, would be ultimately outweighed by the costs associated with the impacts of an actual implementation.

Dissipation with Yielding Restrained Braced Frames (YRBF)

A total of 48 YRBs between 108Tonf and 376Tonf were needed to be part of SRFS.

This alternative uses the same architectural configuration starting point as the BRB alternative. At the $R_d = 2$ and $R_o = 1.5$ had better results than the BRB option because of the difference in overstrength. In this case therefore, engineers proceeded to use a reduction factor of $R_d = 5$ and $R_o = 1.1$ (later confirmed by NLTH) which according to recent scientific results will prevent the structure from considerable damage and, instead of ductility, it would represent the energy dissipated by the seismic brake. Using this factor, it could be expected that the structure would have maximum inelastic drifts of 0.015h and residual drifts below 0.005h with a decent degree of certainty [9]. More information about the design methodology and its validation will be offered in the Methodology of the **part B** [10] document.

With design spectral accelerations around 0.25g, strengthening of columns and beams was less aggressive. The same problem of torsional effects was addressed at lower forces since the Ten-Co in the YRB has smaller overstrength requirements of approximately 1.1x (hence $R_o = 1.1$), in contrast with 2.5x of a BRB. Four corner longitudinal plates along with transversal ones each 25cm with thickness between 0.85cm and 1.26cm were used to reinforce columns capacity, having in mind that concrete assumed ultimate capacity was 200kgf/cm^2 (see Image 8). The same W profile beams were included to warrant a rigid-diaphragm in the short sense (Y).

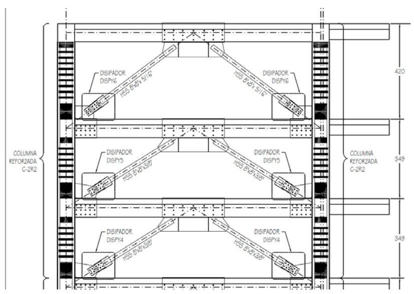

Image 8 Typical arrangement of YRB proposal in the short sense (Y) (left)

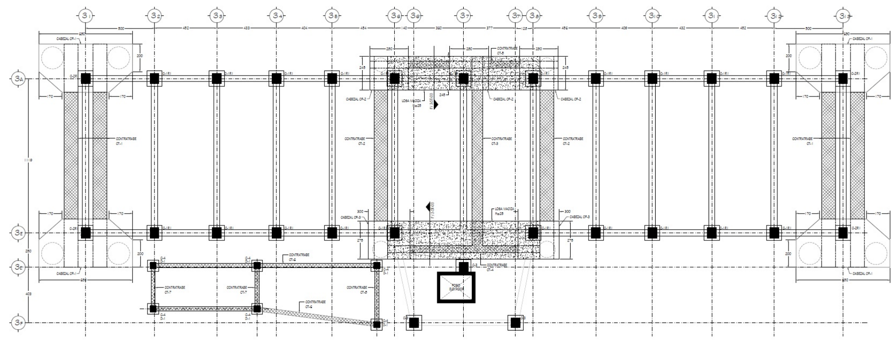

Image 9 Foundation design for YRB proposal, 13 piles

At the same time, lower overstrength in the system meant lower forces to be translated to the final foundation design (see Image 9). Only 13 piles between 100 and 160cm diameter at 20m depth were needed. The whole foundation re-design was less complex that the shear wall and BRB proposals.

The Yielding Restrained Brace (YRB) concept

The concept consists of providing the structure with a brace that does not enter the ductile range and whose stiffness remains constant. At a certain axial force, it will start dissipating energy by the means of fictitious ductility provided by a in-line Tension – Compression seismic brake (Ten-Co). This can be seen as a perfect yielding mechanism that does not suffer from the overstrength problem thus keeping the force constant through out all the axial stroke. In this way, the concepts of yielding and stiffness are decoupled, making the stiffening of structures more efficient. The engineer can add stiffness without making the structure necessarily more expensive with unneeded capacity.

Schematically (see Image 10), the YRB is composed of a common brace connected to a Ten-Co [11]. As its names indicates, it's a in-line Tension-Compression seismic brake (commonly labeled a damper), that when activated, either in tension or in compression, and even under cyclical loading, will have the same behavior when the relationship between force and displacement is plotted. This can be seen in the rectangular shape of its hysteretic loop. It is considered in-line because the friction between special surfaces occurs along the axial axis of the brace.

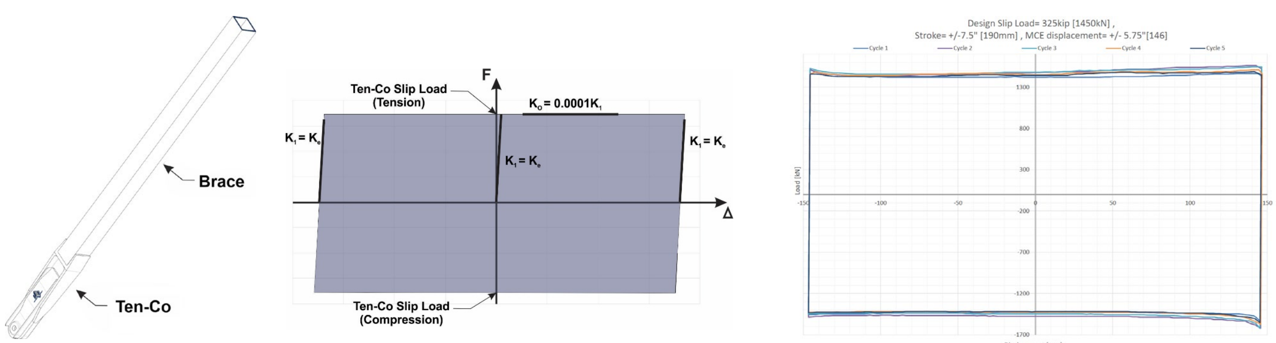

Image 10 Yielding Restrained Brace (YRB) (left). Theoretical Force vs Displacement relationship of the YRB (center). 5 cycles of real Force vs Displacement relationship with less than +/- 15% variation, courtesy of manufacturer.

Conditions enabling the YRB concept

For a YRB to work, engineers knew that certain conditions needed to be met:

1. An in-line seismic brake was needed. Rotational mechanisms were to be avoided. The force in a rotational friction mechanism is not displacement dependant but rather angle dependant. The axial force in the brace that is ultimately translated to the structure will vary with the rotation angle in the mechanism as the mechanical advantage changes (see Image 11).For this reason, a Ten-Co was required.

2. Cycle after cycle, and during the whole stroke, the Ten-Co hysteretic loop must be stable (see Image 10 right). It must be stable as well in the long-term with respect to corrosion and creep (see Image 12). This will warrant the hypothesis of minimal overstrength that has been used for the design of the structural elements.

3. Each and every single Ten-Co should have the same behavior. This way each will activate at the force indicated by the analytical model and the structure will behave as predicted. It will also keep the forces under control at every critical point in the building. This particular assumption requires a 100% production testing program to validate individual slip loads.

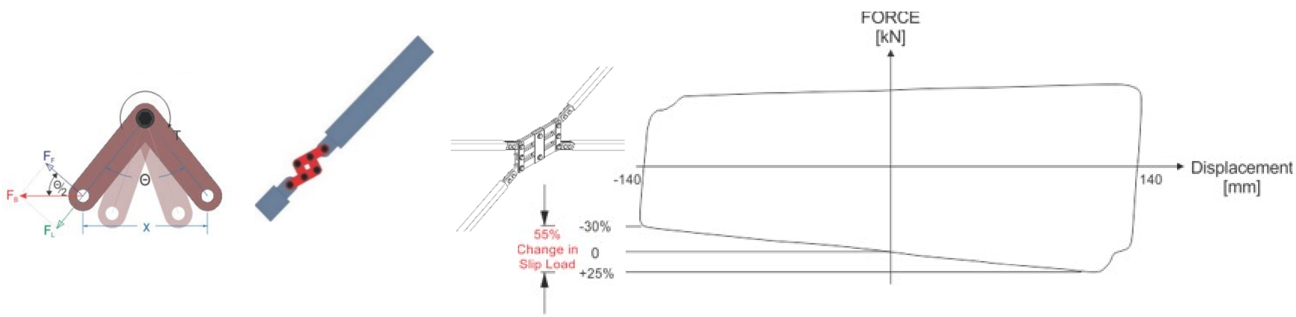

Image 11 Variation in force in rotational mechanisms

After some research, engineers found that a similar system had been used in several countries. In the last 30 years, it had been implemented in a myriad of structures, new and existing, steel and concrete, low-rise [12], mid-rise [13] and high-rise [14]. It was also implemented in commercial buildings [15], industrial facilities [16], institutional [17] and some residential [18]. Engineers contacted the direct manufacturer, of this technology as they had extensive experience with friction technologies in this industry and aerospace.

Displacement and velocity independence

Friction mechanisms have been categorized in most building codes [19] as displacement dependant. However, as can bee seen in Image 10, such dependence does not exist when using an inline friction device. Displacements can vary while the slip force remains constant. Furthermore, in high-quality devices, variations in this force after several cycles are negligible. The assumption of velocity independence must be made carefully however as some surfaces, such as PTFE can have substantial variations in the friction coefficient dependant on velocity [20] Some specialty devices such as the Ten-Co are independent of velocity, as proven in various comprehensive real scale studies [9]: but this cannot simply be assumed. [20]Despite these considerations, codes tend to refer to displacement dependant mechanism as substantially independent of speed [19].

The problem becomes that this current categorization of devices, *displacement* or *velocity dependent*, can mislead the structural consultant to believe that if a device presents displacement dependant characteristics it will be inherently velocity independent and to completely ignore the effects of velocity. For instance, there is currently no provision in codes to account for the very well know effect of high strain rate [4] [3] on cold working of steel which is the main vehicle for energy dissipation in metallic (yielding) energy dissipaters/dampers (e.g. BRBs, TADAS etc.). It is therefore necessary to introduce a third category of *constant force devices*, where devices such as the Ten-Co, whose velocity and displacement independence have been verified at full scale at least once (given the high cost of such tests): can be better categorized.

Long term durability and corrosion

Engineers were also looking to confirm the long-term stability of the Ten-Co's characteristics and performance, specifically the slip load and available stoke. This was especially important in this project given its location facing the sea (high-salinity & humidity). Although the special surfaces suppose to not suffer corrosion, the manufacturer had performed testing on a 200kN specimen to test corrosion concerns. The exterior of the selected specimen had received no additional protection (as is customary for outdoor applications), was selected at random from production and a baseline performance test conducted. The Specimen along with two reference lengths of rebar were sealed into an environmental chamber and cyclically exposed to a highly corrosive warm saline, wet and dry environments to induce corrosion. This type of cyclical testing is based on test methods from car manufacturers was required, as ASTM B-117 type testing produced insufficient corrosion: and therefore, a more aggressive environment was needed. After 2 weeks in the chamber and once the rebar controls were sufficiently corroded (flaking and weight reduction), and the specimen had signs of external corrosion, it was removed and retested. The hysteretic loop of the specimen post exposure to the corrosive salt fog and cyclical environmental conditions can bee seen in Image 12.

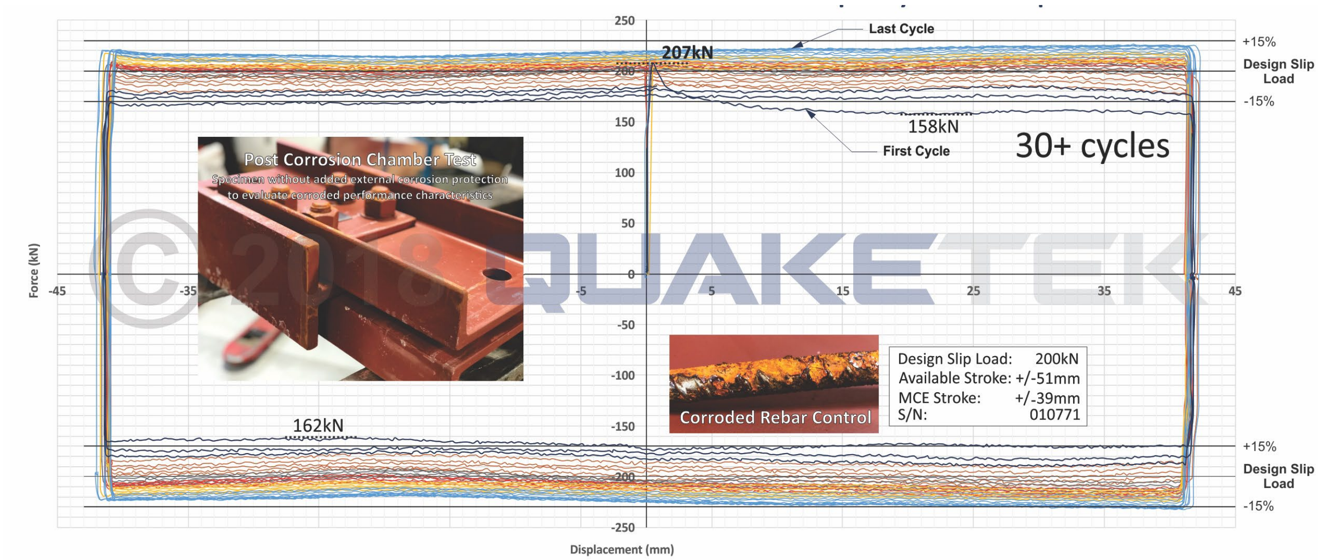

Image 12 Hysteretic loop and Ten-Co condition of 30+ cycles after durability test protocol. Comparison against +/- 15% benchmark

Real scale testing

A very important point to mention is the appropriateness of real scale testing. Effects of velocity, corrosion and difference of static and dynamic friction are not necessarily valid when extrapolated from very reduced scaled specimens. As it has been demonstrated in the past, even simple concepts such as contact area don't hold when scaling, for example; it is known that at the microscopic level the actual area of contact between surfaces is a fraction of the apparent area [21]. Therefore, it would be naïve to believe that more complicated variables such as pressure distributions or machine tolerances can be linearly extrapolated. Scaling friction cannot be taken lightly since it deals with the complex problem of multibody contact [20]. A good analogy would be making lenses and mirrors for the Hubble space telescope, what worked well at small scale was problematic when brought to real scale, a different design and manufacturing methods were required and even then suffered from a flawed mirror [22].

It's certainly concerning when some codes [19] allow for scaled prototype testing, and in worst cases, for production testing (if any) on scaled models. This misleads the structural consultant, who is often not an expert in material science, to believe that the behavior of a device has been properly established from a reduced scale model. It's even more concerning, when these same codes don't offer guidelines regarding scaling. Perhaps this light perspective is the result of the fact that, usually, structural engineers have been trained to think in terms of static equilibrium, such as a slip critical connection, this however tends to incorrectly relate friction devices to static friction by default. When friction is used in a seismic energy dissipater, it is the dynamic friction that governs the amount of Work done [23].

Engineers in this project, were comfortable with the manufacturer [11] that based all the results on full scale testing, from prototype to 100% full force, full displacement production and quality testing. This manufacturer's team with extensive experience in the aerospace industry and responsible for the manufacture of the first seismic damper in North America, and the first friction device in the world to be installed in a building: reported that scaled devices (one order of magnitude or more, e.g. 1/10 scale) often did not have the same friction characteristics. Many of the challenges and phenomena involved in excessive force variations, and durability are apparently remedied in these very small-scale tests or may even pass undetected, which is often not the case at full scale. Such heavily reduced scaling was therefore not considered and to be avoided.

CONCLUSIONS

The retrofit project with YRBs was shown to economically protect the structure against the MCE (2% probability in 50 years) with negligible damage in the existing elements and without the need for post-earthquake maintenance. It produces better results in terms of performance and costs that the other two developed alternatives; shear walls and BRBs. As shown in the Alternatives section, foundation costs can be reduced more than 50%. A Methodology of how to use a force-based linear method with an $R_d \times R_o = 5.5$ for the system, and its respective validation, is presented in **part B** [10].

Regarding the particular use of the YRB, engineers concluded that:

1. For the YRB and its corresponding reduction factor to produce expected results, it should be equipped with a Ten-Co so that the energy dissipation assumed by the factor is available. Therefore, conditions enabling the YRB concept should be strictly met (see page 5), otherwise there may be excessive variation in the design forces assumed

2. The YRB represented a very reliable option when used as SFRS since it allows for the actual testing of the very element causing the energy dissipation against the conditions it will have on the real earthquake. In contrast, other SFRS based out of damage, rely on the assumption that analysis parameters will be closer to the actual behavior.

3. Seismic brake devices, specifically the Ten-Co, may not being properly categorized as *displacement dependent* since the slip force remains constant and therefore independent of displacement (see page 5). On the contrary, it may be more appropriate to label them in a separate category such as *constant force devices.* Some concerns regarding scaling friction are also exposed (see page 6).

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