Improving Seismic Response of Precast Structures Designed with Jointed Connections

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<Subhead 1>

Introduction

Figure 1 depicts a structural member with a jointed connection at the base that utilizes unbonded post-tensioning. When subjected to seismic lateral loading, the member will form a crack and lift off at the base, thereby experiencing a rocking motion. Its lateral load capacity is dictated by the force in the vertical unbonded post-tensioning, which also facilitates the member to re-center with little residual displacements upon load removal. Due to the minimal damage resulting from the concentrated crack opening and participation of no mild steel reinforcement in the moment resistance at the connection interface, the corresponding force-displacement response encloses little energy dissipation that is generally viewed as inadequate for dissipating the seismic energy imparted to the member. As a consequence, such members may experience a long duration of motion and large lateral displacements.

The behavior of precast concrete members with jointed connections was demonstrated experimentally for frames and walls during the Precast Seismic Structural Systems (PRESSS) program[1] in a five-story precast test building. Energy dissipation in both frames and walls was generally enhanced by addition of hysteretic energy dissipating elements. For example, U-shaped stainless steel plates were used in a jointed wall configuration[2] (see **Figure 2a**) to provide supplemental energy dissipation capacity for rocking precast walls. According to the experimental observations, the jointed wall produced excellent seismic performance, exhibited minimal damage, and improved the building's re-centering capacity. More recently, a more cost-effective design of rocking precast walls system was developed and experimentally validated by Sritharan et al.[3]. This system consisted of a Precast wall panel with two End Columns (i.e., PreWEC system), as shown in **Figure 2b**. The panel was connected with the columns using special O-connectors, which enhanced the PreWEC's hysteretic energy dissipation. Following the successful use of the rocking concept in precast concrete systems, similar systems have also been developed for structures of other materials[4, 5].

The above-referenced studies focused on characterizing rocking systems with unbonded post-tensioning under quasi-static loading, but the dynamic response of these systems associated with energy losses due to rocking impacts was ignored, as impact energy loss was considered an insignificant component. Recently, Kalliontzis et al.[7] and Nazari et al.[8] used experiments of free vibration and shake-table testing, respectively, to investigate the energy losses attributed specifically to rocking impacts. To achieve appropriate test conditions and understand the significance of adding hysteretic energy dissipating elements, the tested specimens included no hysteretic energy dissipaters.

Based on these experiments, Kalliontzis et al. proposed a formula that quantifies impact energy losses as a function of the geometric properties of the rocking member, and Nazari et al. measured an average equivalent viscous damping for single rocking walls (SRWs) as low as 1.5%. Despite their low damping capabilities, Nazari et al. noted that SRWs produce satisfactory seismic responses for these systems when subjected to design level earthquakes. However, if these systems are subjected to input motions representing maximum considered earthquakes, their responses may exceed the allowable limits.

Given the current state of knowledge, this study investigates a cost-effective method to increase damping in rocking precast members with jointed connections by placing a rubber layer at the connection interface. Experiments of a precast member with varying class and thickness of rubber layers are used and an analytical investigation is employed to examine the effect of these layers in the seismic response of rocking precast members. Research findings suggest that the use of a rubber layer can increase energy losses in rocking precast members significantly, suggesting that a rubber layer at the jointed connection enables the design of rocking precast members without hysteretic energy dissipaters.

<Subhead 2>

Formulation of energy losses

This section presents the state of knowledge relevant to energy loss resulting from rocking response and some improvements. The fundamental steps toward understanding the seismic behavior of rocking members were undertaken by Housner[9], who conducted an analytical investigation on rigid planar free rocking members that did not include unbonded post-tensioning. Housner assumed that these members can be modelled as single degree of freedom (SDOF) systems, as shown in **Figure 3**.

While experiencing planar rocking, the rigid member of Housner pivots about one of its bottom corners (i.e., points O and O') and its equation of dynamic motion was expressed as shown below:

$$I_o\ddot{\theta} + MgR\sin\left[sign(\theta)\alpha - \theta\right] = -\mathrm{M}R\ddot{u}_g \cos\left[sign(\theta)\alpha - \theta\right] \quad (1)$$

where

g	=	Acceleration due to gravity
I_o	=	Mass moment of inertia of rocking member about pivot point
M	=	Mass of rocking member
R	=	Distance of pivot point from center of gravity of rocking member
$sign(\theta)$	=	Sign of rotation
$\ddot{u}_g$	=	Horizontal ground acceleration
α	=	Slenderness coefficient of rocking member, $\alpha = \tan^{-1}(b/h)$
θ	=	Rotation of rocking member
$\ddot{\theta}$	=	Angular acceleration of rocking member

When $\theta \to 0$, the rigid member impacts with the base. These impacts were assumed by Housner as the only means of dissipating the absorbed seismic energy. The corresponding energy loss was quantified in terms of the coefficient of restitution, *r*, which was defined as the ratio of the kinetic energy of the member just after impact over its kinetic energy just before impact. An expression for *r* was developed by Housner based on the geometric properties of the rocking member. For symmetric rectangular members, this expression is presented in Eq. 2:

$$r = \left(1 - \frac{3}{4}\left\{1 - \cos\left(2\alpha\right)\right\}\right)^2 \qquad (2)$$

However, researchers[10-18] have shown that Housner's formula overestimates the experimentally established energy losses due to rocking impacts. Citing the idealized pivot point to be the main reason for this overestimate, Kalliontzis et al.[7] introduced an improved formula for *r*, which assumes more realistic locations for the pivot points of rocking members and accounts for a finite contact length between the rocking member and the base. This is based on experimental evidence of rocking precast members, including the jointed wall system tested in the PRESSS building. Eq. 3 presents this new formula for symmetric rectangular members.

$$r = \left[\frac{4 - 3\left(\sin\alpha\right)^2\left(1 + k^2\right)}{4 - 3\left(\sin\alpha\right)^2\left(1 - k^2\right)}\right]^2 \qquad (3)$$

where k is the ratio of the distance between the pivot points over the member's width, which may be obtained from experimental data. In the absence of available data, Kalliontzis et al. suggested the use of $k = 0.72$.

Priestley et al.[10] developed an expression to estimate the total energy losses due to rocking motions, which may include energy losses (e.g., due to friction or viscous damping) in addition to those due to rocking impacts, in terms of equivalent viscous damping, ζ. This expression is detailed in Eq. 4:

$$\zeta_{total} = \frac{1}{\pi n} \ln\left(\frac{\theta_o}{\theta_n}\right) \tag{4}$$

where

θ_o = Initial rotation

θ_n = Amplitude of rotation after n impacts

Using Eq. 4 with $n = 1$, the computed equivalent viscous damping corresponds to a time duration of one-half rocking period, which includes one impact.

More recently, an expression for ζ was presented by Makris and Konstantinidis[19], assuming that ζ is a function of r and that all energy losses are attributed to rocking impacts:

$$\zeta_{impact} = -0.34 \ln(r) \tag{5}$$

Eq. 5 was analytically shown by Makris and Konstantinidis to adequately reproduce ζ of Eq. 4 for free rocking members without unbonded post-tensioning when they dissipate energy only during impacts.

Figure 4 presents average experimental[7, 8, 10-18] and theoretical values of energy losses due to rocking impacts expressed in terms of ζ of Eq. 5. For a given value of α, the energy losses due to impacts differ significantly between experiments. For example, when $\alpha = 0.245$ rad and between the ζ values referenced here, the maximum and minimum ζ values differ by 59%. As explained in Kalliontzis et al.[7], these differences may stem from imperfections and different materials used in these experiments, which included concrete, steel, and timber members. Overall, comparing the experimental ζ values with the two theoretical estimates, the formula by Kalliontzis et al. for r provides a significantly improved correlation to the referenced experiments.

<Subhead 3> **Experimental investigation**

Another observation from **Figure 4** is that α of precast flexural members (i.e., beams, column and walls) will be less than about 0.25, implying the corresponding ζ of less than 5%. This has been experimentally verified by Nazari et al.[8] using rocking precast wall panels. Therefore, an experimental investigation was undertaken here to increase the energy dissipation of rocking precast members using a thin rubber layer as the interface material between the rocking member and adjacent connecting element.

Test setup

Figure 5 presents a precast concrete member that was tested in the structural laboratory at Iowa State University under free vibration motions. The member had dimensions of 17.78 cm x 71.12 cm x 242.57 cm (i.e., width x length x height) and was tested on a concrete foundation that had dimensions of 127 cm x 127 cm x 60.96 cm (i.e., width x length x height). Reinforcement details of the member are presented in **Figure 6** and parameters defining its rocking behavior are included in **Table 1**.

To ensure full contact between the rocking member and the foundation surface, a 2.54 cm thick non-shrink grout layer or a rubber layer was used at the top of the foundation. Damage to the precast member was minimized by placing steel angle members along the rocking edges and firmly embedding them into the member using 50 mm long shear studs. These steel elements prevented potential crushing of cover concrete due to impacts. A wood frame was placed as shown in **Figure 5** to prevent out-of-plane movement of the member; gap distances of 2.54 cm in the front and back sides of the member were initially allowed between the member and the wood frame to ensure no contact during planar rocking.

Free vibration tests

An electric pump and a hydraulic jack were used to excite the precast member in free vibration modes, with initial top lateral drifts (ITLD) ranging between 1 and 3%.

Instrumentation

The instrumentation included light emitting diodes (LEDs) that were attached to the surface of the test unit as shown in **Figure 6**. In addition, a string potentiometer was used to obtain an independent measurement of its lateral movement as a function of time and ensure the target ITLDs before initiating the free vibrations. A load cell was placed on top of the member to capture the variation in the post-tensioning force due to lateral displacements. The acquisition system used sampling frequencies as high as 500 Hz.

Interface Materials

The precast member was first tested with a grout layer with specified strength of 70 MPa as the interface material at the jointed connection interface at the top of the foundation. Then three classes of rubber were employed with shore hardness (SH) of 1) 50; 2) 70; and 3) 90. All rubber layers had sectional dimensions of 17.78 cm x 71.12 cm (i.e., width x length). The rubber layers with SH of 70 and 90 had 2.54 cm thickness. Three levels of thickness were used for the rubber layer with SH of 50: 1) 2.54 cm; 2) 1.27 cm; and 3) 0.635 cm.

Unbonded post-tensioning

The precast member was post-tensioned using an unbonded seven-wire strand (Grade 270) with diameter of 15.24 mm and unbonded length of 283.21 cm. The target initial post-tensioning force was 30 kN. Due to losses from anchorage slip, the initial post-tensioning forces were reduced upon removal of the hydraulic jack. **Table 2** presents all values of initial post-tensioning force as they were recorded by the load cell just before the tests. The tendon remained within the elastic response range during all tests and no reduction in the initial post-tensioning force was indicated by the load cell at the end of the tests.

Experimental results

This section presents experimental responses of the six rocking systems summarized in **Table 2**. Experimentally, all systems performed satisfactorily. No damage was observed to the rocking member, interface material layers, or the foundation.

Time-histories of top lateral drift

Figure 7 presents measured time-histories of top lateral drift for all systems and ITLDs of about 2%. **Figure 7a** compares all cases with 2.54 cm thick interface layer and shows that the responses of systems with a rubber interface decay significantly faster than the system with a grout interface; the displacement amplitude of the former approaches zero after about 1 second, while the system with grout continues to oscillate for several seconds. After 2.5 seconds, the top lateral drift of the member with the grout interface decreased only by 50% of the ITLD. **Figure 7b** compares the three top lateral drift responses of the systems that used rubber with SH of 50 and three different thicknesses: 2.54, 1.27, and 0.635 cm.

The top lateral drift amplitudes corresponding to the responses in **Figure 7** are normalized with respect to the ITLD and compared in **Figure 8**. **Figure 8a** shows that drift amplitudes in systems with rubber of SH = 50 and 70 and thickness of 2.54 cm decay similarly, but the amplitude in the system with rubber of SH = 90 approaches zero at about 0.5 seconds earlier. In **Figure 8b**, insignificant differences are seen between systems with SH of 50 and thicknesses of 1.27 and 0.635 cm, but the decay of drift amplitudes was relatively faster when the thickness of 2.54 cm was used.

Equivalent viscous damping

The overall damping capabilities of the systems were investigated by quantifying the corresponding equivalent viscous damping using Eq. 4 with $n = 2$, which estimates ζ due to the total energy losses and can capture variations in ζ with respect to top lateral drift. Experimental results of ζ are presented in **Figure 9** as a function of the top lateral drift. As seen in **Figure 9a**, when grout was used, the measured values of ζ were significantly lower than the systems with rubber, and in several cases they differed by an order of magnitude. Also for practical purposes, there was no significant effect of SH of the rubber on ζ. However, **Figure 9b** indicates that ζ increased with increase in the thickness of rubber.

Table 3 presents average ζ values using the data presented in **Figure 9** with respect to three ranges of top lateral drift: 0-1%; 1-2%; and 2-3%. All measured average values are shown to increase with decrease in top lateral drift. When the rubber layer with SH of 50 is used, ζ increases with increase in the thickness of the rubber layer. In agreement with **Figure 9a**, it is shown here that ζ varies only slightly with respect to the SH of rubber.

Components of energy loss

Per Housner[9], free rocking members with rigid jointed connections exhibit no energy losses due to flexure, hysteresis, or friction at the connections, but all energy losses occur during impacts. As observed by Kalliontzis[20], this assumption compares well with experiments of rocking precast concrete members with unbonded post-tensioning that use grout at the jointed connection and are subjected to ITLDs up to 3%. To investigate the effect of rubber layers in energy losses of precast members, the dominant energy components associated with the rocking response of the members were computed. These included: a) Rotational kinetic energy, K; b) Gravitational potential energy, U_g; and c) Potential energy due to elongation in the unbonded post-tensioning tendons, U_{PT}. These components can be estimated using Eqs. 6-8, with an assumption that the unbonded tendons respond elastically.

$$K = \frac{1}{2} I_o \dot{\theta}^2 \tag{6}$$

$$U_g = MgR\left[\cos\left(\alpha - |\theta|\right) - \cos\left(\alpha\right)\right] \tag{7}$$

$$U_{PT} = \frac{AE}{2L}\Delta L^2 \tag{8}$$

where

A	=	Cross-sectional area of unbonded tendon
E	=	Modulus of elasticity of unbonded tendon
L	=	Unbonded length of tendon
ΔL	=	Total elongation of unbonded tendon
$\dot{\theta}$	=	Angular velocity of rocking member

Using Eqs. 6-8, the total energy content in a rocking member can be estimated using Eq. 9:

$$E_{total} = K + U_g + U_{PT} \tag{9}$$

When impacts are assumed as one mechanism of energy dissipation in the rocking member, the energy losses per impact can be estimated using Eq. 10:

$$\Delta E_{impact} = \left(1 - r\right) K_{impact} \tag{10}$$

where

K_{impact}	=	Kinetic energy of the rocking member just before the impact.

Time-histories of experimentally measured total energy content of the systems with rubber are presented in **Figure 10**. Theoretical responses that assume energy losses only during impacts, as per the coefficient of restitution of Eq. 3, are also included in this figure.

According to the theoretical responses, the total energy content in a rocking rigid system reduces instantaneously due to impacts and remains constant during the rest of the response. Compared with these responses, the measured time-histories differ significantly, as they dissipate the absorbed energy faster and exhibit different behavior during impacts as well as during the non-impact phases of motion.

During impacts, the energy in the systems drops suddenly, which is followed by immediate energy recover. It is suspected that this behavior could be artificial and could stem from the noise in the acquisition system; a similar behavior has been observed by Kalliontzis and Sritharan[21] in free vibration responses of free rocking members without unbonded post-tensioning. Nevertheless, this behavior is not replicated by the analytical responses presented here and in other studies[20, 21] that used refined finite element models of rocking members. During the non-impact phases of motion, the measured total energy content does not stay constant but fluctuates continuously. This is presumably because of the energy transfer occurring between the precast member and the rubber layer. This behavior has also been observed in another experimental study that used a free rocking member with rubber at the member-to-foundation interface, but without unbonded post-tensioning[22].

For better insight into the components of energy loss experienced by the rocking systems with rubber, the time-histories of their kinetic energies are employed to compute the energy losses only due to impacts. **Figure 11** compares measurements of total and impact energy losses, with their difference being attributed to the viscous damping provided by the rubber. This figure shows that impact energy losses were only a portion of the total energy losses; yet energy losses due to viscous damping dominated the overall response. This is confirmed in **Table 4**, which presents the percentages of impact energy losses over the total energy losses, as recorded at the end of the motions. It shows that the impact energy losses increased with increase in the value of SH and decrease in the thickness of rubber. Conversely, it may be stated that as the SH increases and thickness of rubber layer reduces, the viscous damping of the rubber is reduced, increasing the energy loss due to impacts. Nevertheless, in all systems impact energy losses participated by less than 30%.

These comparisons indicate that the use of rubber layers at the jointed connections would enhance the rocking members' energy dissipation capabilities. With the use of rubber layers, rocking precast members dissipate the absorbed energy rapidly and in a continuous manner due to the increased damping provided by the rubber.

Post-tensioning forces

Figure 12 compares the increase in post-tensioning force in the systems with grout and rubber layers due to the member's top lateral drift. It is shown that the use of rubber increases the post-tensioning force as a function of drift than the use of grout. Comparisons between the systems with rubber show that increase in SH and decrease in thickness of the rubber lead to higher post-tensioning forces. The higher post-tensioning forces are mainly due to the reduced neutral axis depth at the connection interface, which leads to higher elongations in the tendon. For example, at a top lateral drift of 2%, the neutral axis of the system with rubber of SH = 50 and 0.635 cm thickness was experimentally measured at 3.6 cm from the member's bottom corner; at the same top lateral drift, the neutral axis of the system with grout was found at 8.9 cm from the member's bottom corner.

<Subhead 4> **Analytical investigation**

This section employs SDOF models to investigate the effect of rubber interface layers in the seismic response of rocking precast members. To accurately represent the dynamic response of these members via a SDOF system, the analysis method by Housner, Eq. 1, is modified to account for the effects of rubber and the re-centering force due to unbonded post-tensioning. An improved SDOF system is verified using experimental data.

Improved SDOF analysis

The improved SDOF analysis assumes that a) there is energy transfer between the precast member and the rubber layer during the non-impact phases of rocking motions; and b) there are energy losses due to viscous damping introduced by the rubber layer in addition to those from impacts. The corresponding equation of motion is produced in Eq. 11:

$$I_o\ddot{\theta} + MgR\left[sign(\theta)\alpha - \theta\right] + PT(\theta) + \Delta \mathrm{E}(\dot{\theta}) = -\mathrm{M}R\ddot{u}_g \cos\left[sign(\theta)\alpha - \theta\right] \qquad (11)$$

where:

a) $PT(\theta)$ accounts for the re-centering force due to unbonded post-tensioning and is computed using Eq. 12:

$$PT(\theta) = \left[PT_i + \lambda\frac{AE}{L}e\right]\lambda b \qquad (12)$$

where

PT_i = initial post-tensioning force

e = elongation of unbonded tendon due to member rotation

with $e = b\sqrt{2}\sqrt{1-\cos\theta}$ [23]. λ is an empirical parameter that is computed based on the mean variations in post-tensioning force, as shown in **Figure 12**. The selected values of λ are included in **Table 5**.

b) $\Delta \mathrm{E}(\dot{\theta})$ is detailed in Eq. 13 and accounts for the energy transfer between the precast member and the rubber layer as well as the energy losses due to viscous damping.

$$\Delta \mathrm{E}(\dot{\theta}) = \mathrm{B}\left[sign(\theta), sign(\dot{\theta})\right]\sqrt{|\dot{\theta}|} \qquad (13)$$

where B is computed per rocking phase (i.e., each rocking phase is defined by a combination of $sign(\theta), sign(\dot{\theta})$) and is expressed as a function of the I_o of the rocking member. The selected values of B are presented in **Table 5**, where the higher (absolute) value per rubber layer corresponds to energy loss and the lower (absolute) value corresponds to energy gain. The highest B in both cases is selected for the rubber with SH of 50 and thickness of 2.54 cm, while the lowest B associated with energy gain is selected for the rubber with SH of 90.

B was established based on experimental evidence of the systems with rubber layers at the jointed connections. This is explained in **Figures 13** and **14** that present experimental responses of typical four phases constituting a full rocking cycle. Respectively, these include a a) phase diagram, which presents the relationship between rotational displacements and velocities of a rocking member; and b) time-history of total energy content.

According to the figures, a rocking precast member with rubber layer loses energy while experiencing the first phase of rocking motion. Subsequently, it impacts with the base, and the member gains energy during the second phase until it reaches its peak displacement and zero velocity. During the third phase, the member experiences energy loss, and it subsequently impacts with the base. It then enters the fourth phase, during which it experiences some energy gain.

Verification

The improved SDOF analysis is implemented to produce free vibration responses of all systems with rubber using the same initial conditions as in the experimental investigation. Comparisons between experimentally measured and analytical time-histories of top lateral drift are presented in **Figure 15**. The figure shows that the SDOF analysis is in good agreement with the experimental responses for all systems. Some deviations occurred only at small drift amplitudes.

Next, **Figure 16** compares the experimentally measured time-histories of total energy content with the corresponding estimates by the improved SDOF approach. The analyses are not only able to accurately estimate the overall energy decays in the systems, but are able to accurately reproduce the responses of total energy content as observed in the experiments. The analyses differ from the experiments only during impacts when there were significant drops in the recorded total energy contents as questioned before. However, these discrepancies did not compromise the accuracy of the overall responses of the systems.

Seismic response: To examine the response of rocking systems with a rubber layer at the connection interface when they are subjected to horizontal ground excitations, the improved SDOF analysis is employed to develop rocking displacement spectra. These spectra enable a demonstration of the effect of using a rubber connection interface on the maximum displacements that rocking systems (i.e., of various slenderness, size, initial post-tensioning force) could experience under horizontal earthquake motions. Two scaled earthquake records from the database in Nazari et al.[24] were used to develop the rocking displacement spectra. Time-histories of the two selected base motions are presented in **Figure 17**.

The rocking displacement spectra corresponding to the two base motions were computed assuming that the precast members were post-tensioned with one unbonded tendon of 15.24 mm diameter. The tendon was assumed to be concentrically placed, which is consistent with the presented experimental investigation and other research studies of rocking precast systems[7, 8, 24, and 25].

The developed rocking displacement spectra account for two values of slenderness ratio: a) *h/b* = 3.41, which corresponds to the test unit of the presented investigation; and b) a higher slenderness ratio of *h/b* = 6.00. Similar to Vassiliou and Makris[23], the initial post-tensioning force in a member of the spectrum is determined based on the ratio of PT_i / Mg , which remains constant across the spectrum. A ratio of $PT_i / Mg = 1.8$ was selected here, which is based on the initial post-tensioning force used for the system with SH = 50 and rubber thickness of 0.635 cm.

Presented in **Figures 18** and **19** are rocking displacement spectra for the two base motions and the range of $1 < 2\pi / p < 5$ seconds, where increase in $2\pi / p$ corresponds to increase in the size of the rocking member. In general, the members considered here exhibit reduced peak drifts with decrease in slenderness. For all spectra, the use of rubber with SH = 90 successfully reduces the peak drift responses compared to the theoretical system that includes only impact energy losses. For instance, during the base motion of Test #15 and *h/b* = 6.00, this system experienced its maximum peak drift of 2.7% for $2\pi / p = 2.0$ seconds, while, for the same value of $2\pi / p$, the theoretical system experienced a peak drift of 5.7%. For the Test #18/1 and *h/b* = 6.00, it experienced its maximum peak drift of 2.6% for $2\pi / p = 2.8$ seconds, while, the theoretical system experienced a peak drift of 6.0% for the same value of $2\pi / p$.

With decrease in slenderness to *h/b* = 3.41, the responses of these two systems became less comparable to each other for $4.5 > 2\pi / p > 3$ seconds, Test #18/1, and the system with rubber of SH = 90 consistently exhibited reduced peak drifts. Due to the base motion of Test #18/1, this system reached a maximum peak drift of 0.3% for $2\pi / p = 2.4$ seconds, and the corresponding drift for the theoretical system was 1.3%. In this spectrum, the theoretical system reached a maximum peak drift as high as 6.4% for $2\pi / p = 3.6$ seconds. Overall, for the presented range of precast members, the use of rubber with SH = 90 reduced the seismic displacement responses, and resulted in peak drifts that were always lower than 3%. Instead, the theoretical system, which was based on the assumption that energy losses occur only during rocking impacts with r estimated per Eq. 3, experienced peak drifts that were as high as 9.9% (i.e., **Figure 19b**).

The rocking systems with rubber of lower SH exhibited different responses. These systems did not reduce the peak drifts as effectively, except for few cases (e.g., $2\pi / p > 3.2$ seconds, h/b = 3.41, Test #18/1). The peak drifts of these systems were comparable to the theoretical system in several regions of the spectra (e.g., $2 < 2\pi / p < 3$ seconds, h/b = 6.00, Test #15; $2.5 < 2\pi / p < 3.5$ seconds, h/b = 6.00, Test #18/1). More important, analyses estimated that several of these precast members may overturn during the shakings, and this happens when the lines of the spectra exceeded the upper limits in the figures.

<Subhead 5> **Conclusions**

The presented research study investigated the use of rubber layers at the jointed connection interface of precast members to economically enhance their damping capabilities and enable their seismic design without hysteretic energy dissipaters. Experimental results showed that a significant increase in these systems' equivalent viscous damping, ζ, can be achieved by incorporating only a thin rubber layer into the jointed connection, without compromising the re-centering tendon force. In particular, the tested members with rubber layers experienced slightly higher tendon forces than the tested member with grout, due to the reduced neutral axis depths at their connection interfaces. When the rubber layers with 2.54 cm thickness were employed, the rocking member achieved average ζ values of 16.4%, 11.6%, and 12.8% for the rubber classes of SH = 50, 70, and 90, respectively, and for top lateral drifts up to 3%.

Following the experimental investigation, an improved SDOF analysis method was developed to estimate the dynamic response of rocking members that use rubber at the connection interface. The improved SDOF analysis was verified using experimental data and employed to investigate the seismic response of precast members with rubber layers using rocking displacement spectra and horizontal base motions with accelerations as high as 1.42g. Analytical results showed that the use of rubber with SH of 90, which was the highest value of SH examined here, can reduce the peak top lateral drifts of the members drastically. For example, when rocking members with h/b = 6.00

and the base motion of Test #15[24] were considered, the use of this rubber layer reduced the maximum peak drift of the spectrum corresponding to the theoretical system by 52.6%. When the *h/b* ratio was reduced to 3.41, the theoretical system reached peak drifts that could be 25 times higher than the peak drifts of the system with the rubber layer of SH = 90 (i.e., when $2\pi / p = 3.6$ seconds, Test #18/1[24]).

In all members, included in the analytical investigation, and for the selected base motions, the peak drifts of members that used rubber with SH of 90 were consistently below 3%. The use of this rubber class achieved experimentally measured ζ values that ranged from 10.5% to 23.9%, and is recommended for improving the damping capacity of precast members with jointed connections.

<Subhead 6> **Acknowledgments**

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<Subhead 9> **Abstract**

While the use of precast members with a jointed connection for resisting seismic lateral loads has gained momentum in recent years, they are not applicable in seismic regions without incorporating supplemental hysteretic energy dissipation elements due to their low energy dissipation capacity. This is because their dominant mechanism of impact damping is perceived to be inadequate to effectively dissipate the seismic energy that may be imparted to them. As a consequence, a precast member designed with jointed connection may experience a long duration of motion and large lateral drifts when subjected to seismic loads. This research study investigates a method that allows these members to dissipate the seismic energy efficiently by having them rock on a rubber interface that is placed at the jointed connection. Experimental tests that examine the use of various classes and layer thicknesses of rubber show that this approach can increase damping in these members significantly. Using experimental data and numerical analyses, this study quantifies the increase in energy dissipation and seismic responses associated with this use of rubber.

<Subhead 10> **Keywords**

Rocking, Coefficient of Restitution, Rubber, Unbonded post-tensioning, Impact, Jointed Connection

<Subhead 11> **Figure captions**

Figure 1. Unbonded post-tensioned member with jointed connection.

Figure 2. Examples of the Jointed Wall and PreWEC systems[6].

Figure 3. A rocking rigid rectangular member as described by Housner.

Figure 4. Experimentally measured and theoretical estimates of ζ due to impact energy losses.

Figure 5. Test unit with a rubber layer.

Figure 6. Reinforcement details of the test unit, and locations of LED sensors and potentiometers, where all dimensions are expressed in cm.

Figure 7. Time-histories of top lateral drifts, including rocking members with: a) layer thickness of 2.54 cm; and b) rubber layer of SH = 50, where Th denotes the thickness of rubber.

Figure 8. Decay of normalized top lateral drift amplitudes of rocking members with: a) layer thickness of 2.54 cm; and b) rubber layer of SH = 50, where Th denotes the thickness of rubber.

Figure 9. Equivalent viscous damping, ζ, of rocking members with: a) layer thickness of 2.54 cm; and b) rubber layer of SH = 50, where Th denotes the thickness of rubber.

Figure 10. Time-histories of total energy content of rocking members with rubber layers in comparison with theoretical responses that include energy losses only due to impacts.

Figure 11. Time-histories of total and impact energy losses in rocking members with rubber layers.

Figure 12. Increase in post-tensioning force due to lateral displacements of the rocking member with grout and a) rubber layer thickness of 2.54 cm; and b) rubber layer of SH = 50, where Th denotes the thickness of rubber.

Figure 13. Phase diagram during a rocking cycle of the system with rubber of SH = 70.

Figure 14. Total energy content during a rocking cycle of the system with rubber of SH = 70.

Figure 15. Comparisons of top lateral drift responses between experimental results and improved SDOF analysis.

Figure 16. Time-histories of total energy content in systems with rubber layers in comparison with the improved SDOF analysis.

Figure 17. Time-histories of base motions[24] used to develop rocking displacement spectra.

Figure 18. Rocking displacement spectra for the base motion of Test #15.

Figure 19. Rocking displacement spectra for the base motion of Test #18/1.

<Subhead 12> **Tables**

Table 1. Parameters defining the rocking motion of the test unit.

M, kg	*R*, cm	*α*, *rad*	**p*, rad/s
963.2	126.4	0.29	2.41

**p* is the dynamic parameter[19] associated with rocking motion of the test unit, where $p = \sqrt{\frac{3g}{4R}}$.

Table 2. Initial post-tensioning force per material layer as recorded by the load cell just before the tests.

Material layer	Thickness, cm	Initial post-tensioning force, kN
1. Grout	2.54	17.8
2. Rubber, SH of 50	0.635	16.9
3. Rubber, SH of 50	1.27	22.2
4. Rubber, SH of 50	2.54	20.0
5. Rubber, SH of 70	2.54	24.0
6. Rubber, SH of 90	2.54	26.9

Table 3. Experimentally measured average values of ζ with respect to three top lateral drift ranges.

		Measured average values of ζ per drift range		
Material layer	Thickness, cm	2-3%	1-2%	0-1%
1. Grout	2.54	0.018	0.014	0.035
2. Rubber, SH of 50	0.635	*n.d.	0.065	0.073
3. Rubber, SH of 50	1.27	0.064	0.072	0.093
4. Rubber, SH of 50	2.54	0.116	0.117	0.198
5. Rubber, SH of 70	2.54	0.094	0.107	0.126
6. Rubber, SH of 90	2.54	0.104	0.119	0.184

*this range of top lateral drifts was not included in the tests.

Table 4. Participation of impact energy losses over total energy losses in rocking members with rubber layers.

Material layer	Thickness, cm	Percentage of impact energy losses, %
Rubber, SH of 50	0.635	29.4
Rubber, SH of 50	1.27	26.0

Rubber, SH of 50	2.54	18.9
Rubber, SH of 70	2.54	23.0
Rubber, SH of 90	2.54	29.7

Table 5. Selected parameters of improved SDOF analysis.

Rubber class	Thickness, cm	λ	$*\mathrm{B}[+,-]$	$*\mathrm{B}[+,+]$	$*\mathrm{B}[-,-]$	$*\mathrm{B}[-,+]$
SH of 50	0.635	0.90	-6.6 I_o	-5.3 I_o	5.3 I_o	6.6 I_o
SH of 50	1.27	0.88	-8.6 I_o	-6.9 I_o	6.9 I_o	8.6 I_o
SH of 50	2.54	0.85	-12.5 I_o	-10.0 I_o	10.0 I_o	12.5 I_o
SH of 70	2.54	0.90	-11.6 I_o	-8.9 I_o	8.9 I_o	11.6 I_o
SH of 90	2.54	1.00	-7.8 I_o	-2.0 I_o	2.0 I_o	7.8 I_o

*expressed in $kN-mm-\sqrt{s}$