PSEUDO-DYNAMIC TESTING OF RC FRAME WITH SOFT-STORY STRENGTHENED USING METALLIC DAMPERS

Romanbabu M. Oinam and Dipti Ranjan Sahoo

ABSTRACT

Existing reinforced concrete (RC) buildings with open ground story and designed only for gravity loads are highly vulnerable to collapse or severe damages under earthquake excitations. Suitable strengthening techniques need to be adopted in order to improve the seismic performance of such deficient structures. In this study, an experimental investigation has been carried out on a single-bay double-story RC frame specimen with open ground story. The test frame is fitted with a metallic yielding device, termed as combined yielding damper (CMD), as supplemental energy dissipation device so as to reduce the seismic demand on the primary RC frame. The design of CMD is carried out based on energy-balance concept in order to achieve a predefined target drift and yield mechanism of structure. Pseudo-dynamic (PsD) testing has been conducted for the scaled recorded ground motions to evaluate the seismic performance of the test specimen. The main parameters investigated are the hysteretic response, lateral load resisting capacity, and mode of failure. A numerical model for the test specimen has been developed using OpenSees software to predict the seismic response. Test results showed that the soft-story mechanism in open ground story RC frame is significantly controlled using CMDs as passive energy dissipation devices.

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Pseudo-dynamic testing of RC frame with soft-story strengthened using metallic dampers

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ABSTRACT

Existing reinforced concrete (RC) buildings with open ground story and designed only for gravity loads are highly vulnerable to collapse or severe damages under earthquake excitations. Suitable strengthening techniques need to be adopted in order to improve the seismic performance of such deficient structures. In this study, an experimental investigation has been carried out on a single-bay double-story RC frame specimen with open ground story. The test frame is fitted with a metallic yielding device, termed as combined yielding damper (CMD), as supplemental energy dissipation device so as to reduce the seismic demand on the primary RC frame. The design of CMD is carried out based on energy-balance concept in order to achieve a predefined target drift and yield mechanism of structure. Pseudo-dynamic (PsD) testing has been conducted for the scaled recorded ground motions to evaluate the seismic performance of the test specimen. The main parameters investigated are the hysteretic response, lateral load resisting capacity, and mode of failure. A numerical model for the test specimen has been developed using OpenSees software to predict the seismic response. Test results showed that the soft-story mechanism in open ground story RC frame is significantly controlled using CMDs as passive energy dissipation devices.

Introduction

Reinforced concrete (RC) frames infilled with masonry walls in all stories except the first (ground) story is one of the preferred construction practices in most developing countries. This type of construction provides several functional and architectural advantages, such as, parking, garages, storage, and other commercial activities. These buildings if designed without considering the seismic load effects are more vulnerable to severe damages and complete collapse under earthquake excitations [1]. The presence of masonry infills in upper stories of these buildings results in the higher lateral strength and stiffness than the first story primarily due to the contribution of in-plane axial strength and stiffness of masonry walls. This leads to the concentration of lateral displacements only at the ground story with negligible inter-story displacements of upper stories under earthquake excitations. Shear wave of earthquakes transmitted into the upper stories of the building by the soft first story is reflected at the top of the building, which causes an amplified amplitude of net lateral force at the first story level [2]. If the first story columns are not designed and detailed for this amplified levels of lateral force and displacement demand, as in the case of non-ductile RC frames, these buildings would undergo complete collapse even under moderate earthquakes.

To enhance the lateral strength and stiffness of such existing open ground RC buildings,

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several conventional strengthening techniques have been proposed as local-modification strategy [3]. These include concrete jacketing, steel jacketing, steel caging, external pre-stressing, fiber-reinforced polymer wrapping on deficient RC columns. Passive control devices are often used in the global-modification strategy to control the excessive damage/collapse of structures under earthquake excitations by reducing the seismic demand on the frame members through the supplemental energy dissipation and damping. Metallic yielding devices possess excellent lateral strength, deformability, and energy dissipation potential under cyclic loading. Conventional steel braces and buckling-restrained braces (BRBs) based on the principle of axial yielding/buckling of metallic elements have been adopted to enhance the seismic performance of deficient RC frames [4]. The effectiveness of metallic dampers based on flexural yielding, shear yielding and combined yielding of steel/aluminum plates have been investigated in improving seismic response of the deficient RC frames [5].

Past studies on the evaluation of effectiveness of seismic strengthening techniques have mostly focused on the findings of slow-cyclic testing of small-scale specimens. The behavior of large-scale strengthened RC specimens under dynamic loading conditions is rather limited. Further, in the absence of properly-validated numerical model, it is increasingly difficult to accurately predict the seismic response of strengthened frames. In this study, pseudo-dynamic (PsD) testing has been conducted on a large-scale one-bay two-story RC frame for varying amplitudes of a recorded ground motion at both un-strengthened and strengthened stages. The test frame represents a typical open ground story structure in which the masonry infill wall is only present at the top story level. The test frame is strengthened using a combined metallic yielding damper (CMD) as the passive energy dissipating device at the soft-story level. A numerical model has been developed using a computer software OpenSees [6] to predict the seismic response of the un-strengthened and strengthened RC frames. The results of numerical study are compared with the test results.

**Pseudo-dynamic Test**

Pseudo-dynamic (PsD) method is adopted as an alternate to the shake-table method to evaluate the seismic performance of structures economically. PsD test combines the realism of shaking table test and quasi-static test. In this method, varying displacements are applied slowly to the test structure. However, during testing, the motions and deformations observed in the test structure are used to infer the inertial forces that the structure would have exposed to the actual earthquake. This information is then fed back into a control engine so as to determine and adjust the effective dynamic displacements that must be applied onto the structure. These pseudo-dynamic forces are typically accomplished by means of actuators pushing against a large reaction frame. This method has the advantage of testing large and tall structures with center of mass well above the base, which normally cannot be tested on a shake-table for evaluating their seismic performance [7]. As this method involves the application of dynamic forces in an equivalent static means through static actuators, close monitoring of the structural behavior including crack initiation, crack growth and stiffness degradation becomes possible. The drawback in such a hybrid method is the lack of simulation of strain rate effects which may not be critical under seismic loads. Also, the method is time consuming due to the requirement of iterative procedure in solving the governing equation of motion under the dynamic loading considering the measured properties of the structures. Fig. 1 shows a schematic representation of PsD testing procedure and related flow chart.
Experimental Investigation

An interior bay of a non-ductile five-story four-bay prototype RC frame with open ground story [2] has been considered for this experimental study. Test specimen as shown in Fig. 2 (a) represents the half-scale model of bottom two-story of the prototype frame. The size of frame members and the amount of reinforcement steel in the test specimen are finalized based on geometric similitude using a scale factor of 0.5 in the respective parameters of the prototype frame. Thus, dynamic similitude relationship has not been maintained between the test specimen and the prototype frame. Test specimen is 4.0 m wide and 3.8 m high with columns of 200 mm×200 mm in size and beams of 200 mm×280 mm in size. Depth of beam includes 60 mm thick RC slab of 1.0 m wide at both floor levels. The longitudinal reinforcement in columns is 2.31% along with 8 mm dia. stirrups at a spacing of 200 mm on centers. Shear stirrups in beams are placed at 125 mm and 150 mm on centers at the end and central segments. Fig. 2 (b) shows the overall test set-up of the test frame.

Cement concrete of 28-days characteristics cube compressive strength of 25 MPa is used in the construction of the test frame. High-yield strength thermo-mechanically-treated (TMT) steel bars are used as the longitudinal and transverse reinforcement in the frame member. Tensile test results showed the yield and ultimate tensile strengths of TMT bars as 405 MPa and 597 MPa, respectively. The measured cube compressive strength of concrete at the day of testing is found to
be 40.18 MPa. Half-scale hand molded bricks are used in the masonry infill panel. The measured compressive strength of masonry prism is noted as 15.9 MPa.

Passive energy-dissipating device, CMD consists of a web (shear) plate and two end (flexure) plates placed along and normal to the direction of lateral force, respectively. This results in the progressive yielding of these plates under lateral loading, primarily due to the difference between the in-plane shear stiffness of web plate and the flexural stiffness of end plates. It has excellent energy dissipation, lateral resistance, and displacement ductility capacity under cyclic loading [8]. The design of CMD has been carried out using energy balance concept proposed by Goel and Chao [9]. A target drift of 2.0% and the formation of plastic hinges in beams and column bases as the target yield mechanism is considered as the acceptable performance objective in this study. A detailed design procedure for determining the size of flexure and shear plates of the chosen CMD can be found elsewhere [5,8]. Fig. 3 shows the details of CMD of overall dimension of 200 mm × 500 mm used in this study. A shear plate of 3.2 mm thickness is attached to the base plates at the top and bottom using the bolted connections. Two flexure plates of 6 mm thickness are welded to the base plates. Table 1 summarizes the measured values of yield stress, ultimate stress, and ultimate strain of steel plates of CMD.

![Diagram of CMD](image)

**Figure 3.** Details of CMD: (a) Elevation and sectional views and (b) Test specimen

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield Strength (MPa)</th>
<th>Ultimate Strength (MPa)</th>
<th>Ultimate Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural plate</td>
<td>280.1</td>
<td>372.8</td>
<td>21.0</td>
</tr>
<tr>
<td>Shear plate</td>
<td>239.8</td>
<td>342.5</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Two servo-controlled hydraulic actuators (capacity = 250 kN; stroke length = 250 mm) are used to apply the lateral displacements at the beam-slab levels of specimen. The possible out-of-plane movement of test specimen under the lateral loading is restrained by means of the lateral supporting systems as shown in Fig. 2(b). Concrete cubes are placed at the top story slab level, while the concrete beams are placed at the bottom story slab level as gravity load. Axial stress in columns under the applied vertical loads is found to be 10% of their axial capacity. PsD testing is conducted by using the scaled 1940 El-Centro ground motion. The scaling factors are considered as 0.75 and 1.0 for the un-strengthened and strengthened frames with the corresponding PGA values of 0.27g and 0.36g, respectively. Fig. 4 shows the unscaled acceleration-time history of 1940 El-Centro Earthquake and comparison of response spectra with code-specified design spectrum [10]. The coefficients of stiffness matrix of the specimen are computed experimentally.
applying a unit displacement at one floor keeping the other fixed and measuring the applied/resisting forces at all these floor levels and vice versa. Hence, both actuators are used in the displacement-control mode. Initial stiffness \((K)\), mass \((M)\), and damping \((C)\) matrices of the test frame at the un-strengthened and strengthened stages are determined as follows:

\[
K = \begin{bmatrix} 29.80 & -26.94 \\ -26.94 & 26.94 \end{bmatrix} \text{kN/mm};
M = \begin{bmatrix} 3398 & 0 \\ 0 & 4768 \end{bmatrix} \text{kg};
C = \begin{bmatrix} 0.027 & -0.019 \\ -0.019 & 0.019 \end{bmatrix} \text{kN-s/mm (Un-strengthened)}
\]

\[
K = \begin{bmatrix} 54.7 & -18.7 \\ -18.7 & 18.7 \end{bmatrix} \text{kN/mm};
M = \begin{bmatrix} 3456 & 0 \\ 0 & 4768 \end{bmatrix} \text{kg};
C = \begin{bmatrix} 0.0423 & -0.0103 \\ -0.0103 & 0.0273 \end{bmatrix} \text{kN-s/mm (Strengthened)}
\]

![Figure 4](image.png)

**Experimental Results**

Fig. 5(a) shows the floor displacement-time history response of the un-strengthened and strengthened frame under 75% and 100%-scaled El-Centro ground motions, while Fig. 5(b) shows the hysteretic response for the same ground motion. The un-strengthened frame exhibited a base shear value of 50.0 kN with a peak floor displacement 11.80 mm. The frame showed some nonlinear behavior. Few major cracks are noted in the columns near the footing and beam-column joint and the maximum width of crack is measured to be 1.0 mm. Under 100%-scaled El-Centro ground motion, the peak values of base shear and floor displacement of the strengthened frame are noted as 82.4 kN and 2.7 mm, respectively. Minor horizontal cracks are observed at the interfaces of masonry walls near the beam-to-column joints. The hysteretic response of the strengthened frame is nearly linear as the imposed loading (mass) on the test specimen is smaller than the value required as per the simulative relationship. The results of PsD tests are used to validate the developed numerical model for the test frame. Slow-cyclic test is conducted to evaluate collapse performance of the strengthened frame as per the displacement history [11] shown in Fig. 6(a).

Fig. 6(b) shows the lateral strength (base shear) vs. top floor displacement response of the strengthened frame under cyclic loading. Nearly-symmetric and stable hysteretic response without any significant pinching is noted. The inelastic response is initiated at 0.21% (3.31 mm) drift level. The peak value of lateral strength is noted as 212.86 kN at 1.65% drift level. The failure of the frame is noted at the first cycle of 2.3% first story drift level. The wider hysteretic loops noted for this frame confirmed the significant contribution of CMD in resisting the cyclic lateral load. Fig. 7 shows the shear failure of column and the deformed configuration of CMD at 2.3% drift level.
Figure 5. Test specimen response in un-strengthened and strengthened conditioned under 75%, and 100%-scaled El-Centro ground motion (a) floor displacement response and (b) hysteretic response.

Figure 6. (a) Displacement profile and (b) hysteresis response of strengthened test frame.

Figure 7. Damaged on test specimen and CMD under cyclic load (a) shear damaged on column and (b) inelastic shear plate buckle on CMD.
Numerical Study

A numerical model is developed using computer simulation platform software called OpenSees [6] to predict the seismic performance of the test specimen at various stages. The modelling of reinforced concrete (RC) members is relatively complex due to the multiple modes of failure including the cracking, crushing, and bond-slip failure. The proposed modelling technique, therefore, considered the axial force-bending moment interaction, flexure and shear behavior, bond-slip characteristics, and pinching effect of RC members as well as the interaction between the strengthening elements and concrete members. The details of numerical modelling of RC frame under cyclic loading using OpenSees software can be found elsewhere [2]. Fig. 8(a) shows distribution of above mentioned elements in the modelling. Displacement-based beam-column elements with fiber sections are used to model the RC frame members. Concrete02 and pinching4 materials are used to model the concrete and reinforcing steel, respectively. Tensile strength of concrete is considered as 10% of peak compressive strength. Masonry infill walls are modelled as the three-strut elements as proposed by Crisafulli and Carr [12].

![Figure 8](https://via.placeholder.com/150)

**Figure 8.** Modelling techniques (a) element distribution and (b) force deformation values of CMD used in the modelling

CMD is modelled as the zero-link elements using “uniaxial hysteretic material”. There is a significant difference between the lateral stiffness of flexure plates and the in-plane shear stiffness of web plates of CMD. Since the yielding of these plates may not occur at the same drift level, a tri-linear backbone model has been adopted to consider the sequential yielding behavior of CMD. The yield strength, elastic buckling strength and inelastic buckling strengths of CMD depend on the aspect ratio and depth-to-thickness ratio of plates. A detailed procedure for the design of CMD can be found elsewhere [5,8]. Fig. 8(b) shows the multi-linear modelling of backbone curve of hysteretic response of CMD. Braces are modelled as elastic truss elements, whereas the steel collars, being load-transferring elements, are modelled as the rigid links [13].

Numerical Results and Discussion

Numerical model of the test frame is subjected to the same level of gravity load and scaled ground motions/displacement history as applied during the experiments. The predicted seismic response of the test specimen is compared with the test results. Fig. 9 shows the comparison of the displacement-time history and hysteretic response for the un-strengthened and strengthened
specimen under 75% and 100%-scaled ground motions. Fig. 10 shows the collapse results of un-strengthened frame predicted from numerical study. Both the floor displacement-time history and the hysteretic response predicted by the numerical model successfully matched with the test results. During the 75% El-Centro ground motion, the maximum floor displacement of the un-strengthened frame is noted as 11.8 mm in the experiment, whereas the numerical model predicted a value of 12.6 mm indicating a maximum difference of 6.8%. Similarly, the peak values of base shear are noted as 50.0 kN and 42.5 kN in the experiment and numerical model, respectively. Under the 100%-scaled El-Centro ground motion, the strengthened frame exhibited the maximum floor displacement of 2.7 mm against the predicted value of 2.8 mm. The maximum base shear for the experimental frame is noted as 41.4 kN; whereas the numerical model predicted a base shear value of 44.7 kN. This shows that the proposed numerical model successfully predicted the seismic response of the test specimen.

![Figure 9. Comparison of (a) floor-displacement and (b) hysteretic response of test frame](image)

Using this numerical model, collapse performance of un-strengthened frame has been investigated. Fig. 10 shows collapse response of un-strengthened frame at 150%-scaled El-Centro ground motion. Shear failure of ground story columns is noted indicating the expected soft-story hinge mechanism. The maximum displacement of top floor level in push and pull direction is 24.6 mm and 23.2 mm respectively, which correspond to the ground floor story drift of 1.53% and 1.45%, respectively. The maximum base shear is recorded as 62.5 kN and 60.0 kN in push and pull direction. Fig. 11 shows the comparison of experimental and numerical results for the strengthened frame under slow-cyclic load loading in terms of hysteresis response and backbone curve. The numerical model predicted the peak lateral strength of 208.7 kN which matched well the experimental value with a maximum difference of about 5% only. The numerical model captured the mode of failure of the strengthened frame as observed during the experiment, which is triggered due to the shear failure of ground story columns.
Summary and Conclusions

The adopted strengthening scheme enhanced the lateral strength, stiffness, energy dissipation, and drift capacity of the non-ductile RC frame with soft first story. The significant contribution of CMDs to the total dissipated energy of RC frame reduced the pinching effect in the hysteretic response of the RC frame. The numerical models successfully predicted the lateral strength, peak floor displacement, energy dissipation, and mode of failure of the test frame under the seismic loading. The modelling technique can capture the shear force-deformation behavior, bond-slip characteristics, and pinching effect in addition to the axial force-bending interaction in the RC frame members. Further study is required to investigate the effectiveness of the adopted strengthening technique in high-rise structures with open ground story considering the influence of masonry infill walls in the upper stories.

References


