Full Scale Testing for Seismic Upgradation of Open Ground Storey RC Buildings using Aluminum Shear-Yielding Dampers

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SUMMARY:
Open ground storey (OGS) buildings have consistently shown poor performance in the past earthquakes primarily due to high rotational and shear demands imposed on ground storey frame members. The present study focuses on the effectiveness of the Aluminum Shear-Yielding Damper (ALSYD) used for the strengthening of such RC buildings through a full-scale test of a single-storey single-bay frame. A 5.5 m wide and 3 m high frame strengthened with ALSYD was tested under slow-cyclic displacement-controlled loading protocol as per FEMA 461. A repeat test was also performed on the frame after replacing the damaged ALSYD unit. The ALSYD frames exhibited stable and non-pinched hysteretic response up to the desired drift level corresponding to useable shear strain limit of 20% in ALSYDs. Hysteretic damping values for ALSYD frames was about 16% and the behavior of the frame with initial and replaced units was similar at all levels of the loading.

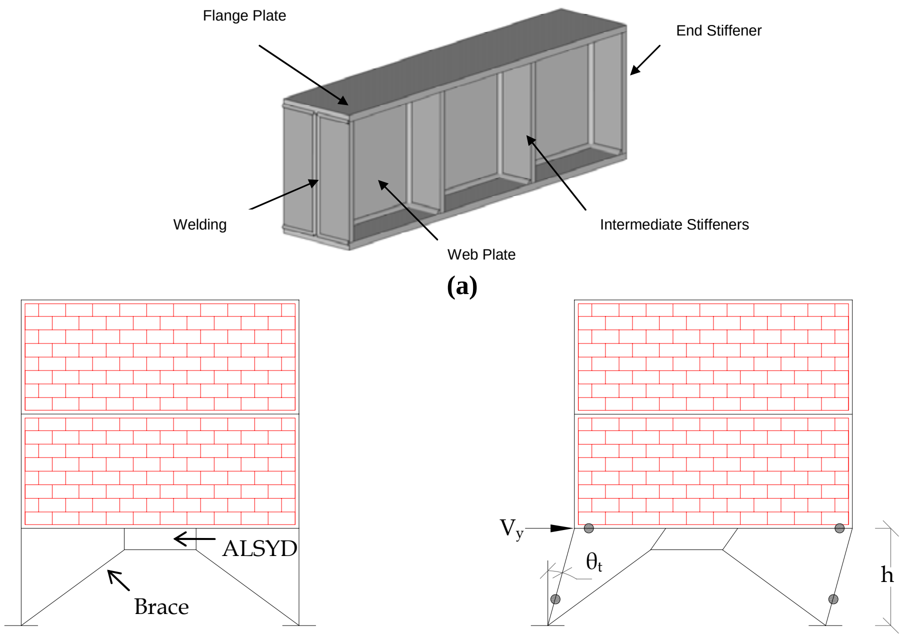
Keywords: Full Scale Testing, Seismic upgradation, Shear-yielding damper, Open ground Storey RC Building

1. INTRODUCTION

Masonry infills are quite common in Reinforced Concrete (RC) structural frames, however, when their absence in a particular story causes undesirable irregularity with respect to lateral strength and stiffness. Open Ground Storey (OGS) buildings have a main advantage in terms of usage of the open storey as a parking area. Such building acts as an inverted pendulum during earthquakes creating high rotational and shear demands on ground storey beams and columns, making it susceptible to greater amount of damage including total collapse of ground storey in a side sway pattern. Designing of OGS building using Indian Code IS 1893 (BIS, 2002) methods is uneconomical on account of large frame member sizes and addition of shear walls. Also these provisions are quite ad-hoc and lack supporting analytical or experimental evidence. There is a need to develop alternate strengthening techniques for such OGS buildings.

Aluminum Shear-Yielding Damper (ALSYD) is a passive energy dissipation device which uses metallic hysteresis to dissipate energy. It is an I-shaped device made up of low yield aluminum alloy which is designed to yield in shear mode. The soft alloys of aluminum has low yield strength and a very good post-yield strain-hardening behavior. The section can be a rolled I-section or fabricated by welding aluminum plates. Fig. 1.1 shows the details of the ALSYD and its working in an OGS of RC frame with masonry infills in upper stories. The device is placed in such a way that the earthquake induced inertia forces cause shear deformation in the device. The yield force for the ALSYD is desirably kept low in order to minimize the amount of force transferred to primary load carrying members and thus, minimize the damage to these members during seismic events.

The concept of ALSYD was introduced by Rai and Wallace (1998) for the purpose of enhancing the seismic performance of Ordinary Concentric Braces Frame (OCBF) systems. Jain et al. (2008) experimentally tested ALSYD sub-assemblages and observed full and stable hysteretic loops up to 20% shear strain in ALSYD webs without any pinching. Sahoo & Rai (2009, 2010) performed slow cyclic tests on a 1:2.5 scale RC frame model for retrofitting using different combinations of ALSYD, column jacketing and column caging and obtained a maximum of 15% shear strain in ALSYD webs. The present study is aimed at examining the effectiveness of ALSYD in enhancing lateral load performance of RC frames and verifying the working of various structural connections for satisfactory transfer of forces in a full-scale test.



(b)

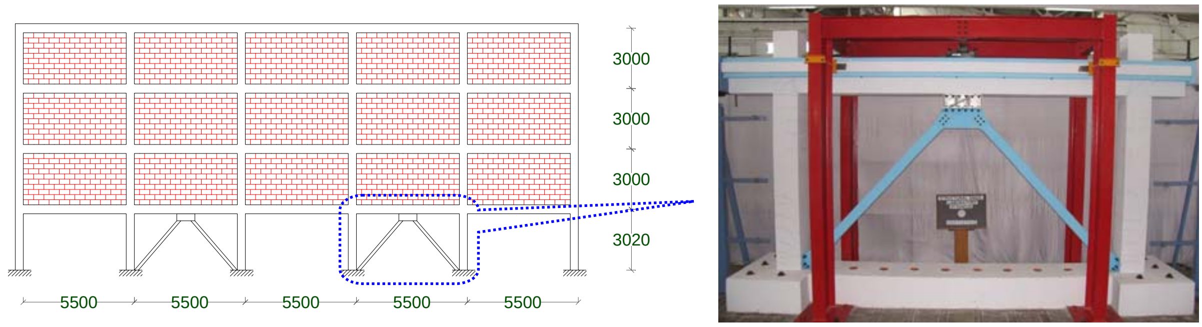
Figure 1.1 (a) Details of ALSYD and (b) Deformation pattern of OGS building with ALSYD under lateral loads

2. DETAILS OF TEST FRAME

A full-scale single bay-single storey RC frame, representing the ground storey of an OGS-ALSYD building, was fabricated for the purpose of experimental testing. It was meant to replicate an internal bay of the frame of a 5-story study building which has the ALSYD system as shown in Fig. 2.1(a). The frame was designed for seismic loads as ordinary moment resisting frame located in seismic zone IV (PGA = 0.24*g*) of IS 1893 (BIS, 2002). Though frame members do not meet the capacity design requirements, they were provided with other typical seismic details. All reinforcement bars had standard end hooks including 135 degree hooks for the confinement bars. Both column and the beam had closely spaced shear reinforcement near the joints as shown in Fig. 2.1(b).

The ALSYD units were sized following the performance based plastic design method as proposed by Leelataviwat et al. (2002) and later developed for hysteretic behavior of ALSYD by Sahoo (2008). The general dimensions of ALSYD is shown in Fig. 2.2, which is made by welding two Aluminum Association I 8×7.02 section of grade 6061-T6. Aluminum stiffeners of 10 mm thickness were welded individually to both I-sections to make three panels with aspect ratio of unity. The SHS 150×180×5 mm was chosen for brace section which was fitted with the cap plate-fork plate assembly to facilitate connections with gusset plate as shown in Fig. 2.3. The details of the design are presented elsewhere (Mehta, 2011).

For the purpose of transfer of lateral forces from the frame to the ALSYD, an embedded bolt plate assembly was placed in the beam reinforcement cage prior to concreting to receive the ALSYD unit. Similarly, the forces from each brace were transferred to the column using embedded bolt plate assembly placed inside the column and footing reinforcement cages prior to concreting (Fig 2.4).



(a)

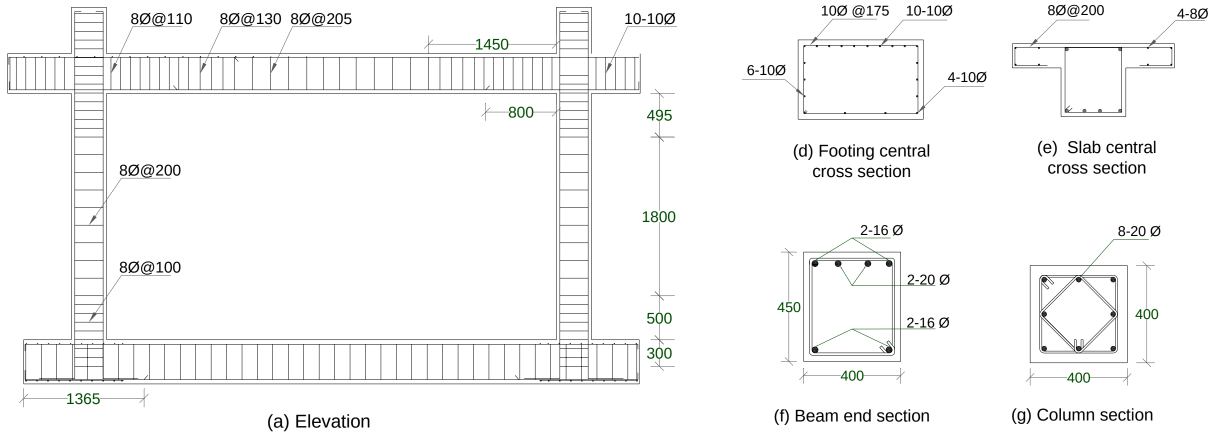


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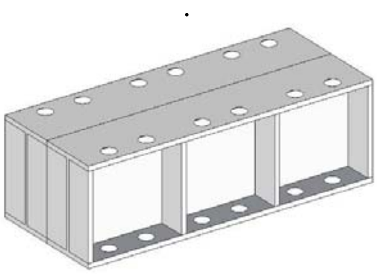
Figure 2.1 (a) Experimental bay from the ALSYD strengthened OGS building frame and (b) Test frame reinforcement details.



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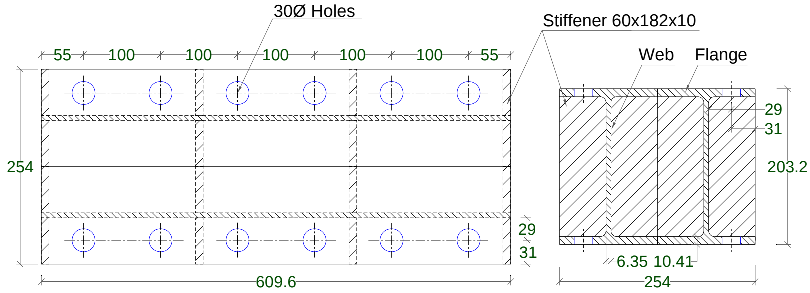
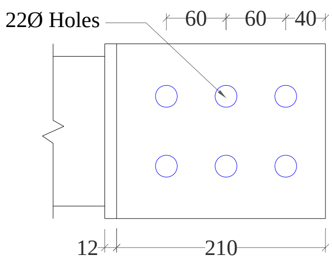


(b)

Figure 2.2 (a) 3D view of ALSYD and (b) details of plan and side elevation

(a)



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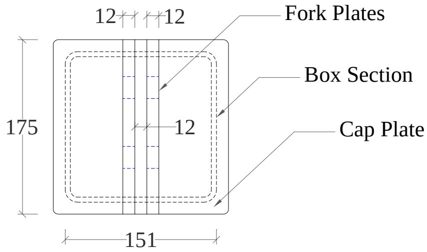


(c)

Figure 2.3 Details of bracing (a) view showing the brace end connection, (b) front elevation and (c) cross-section

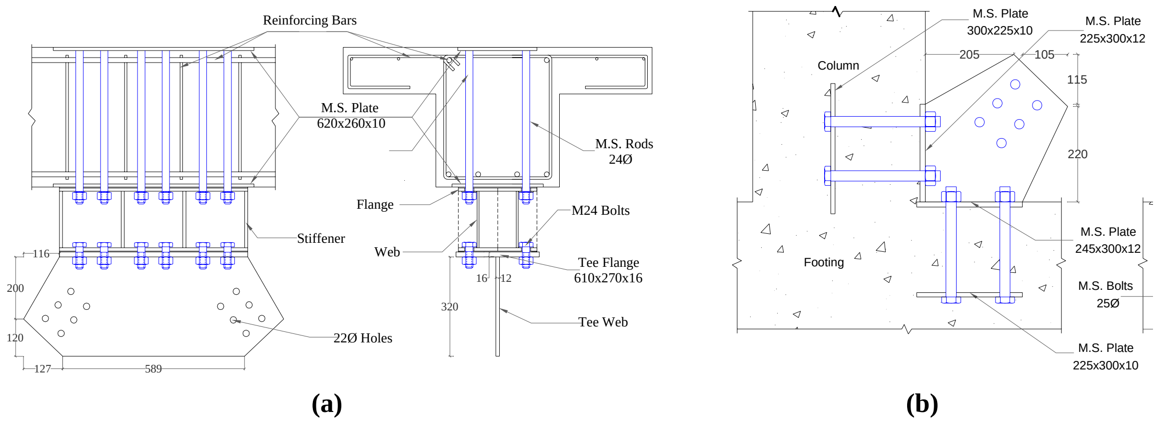


Figure 2.4 Structural details for connection of RC beam, ALSYD and braces (a) plan and (b) side elevation.

The stress-strain behaviour of various materials used in test specimens is shown in Fig. 2.5. The average yield and ultimate strength of annealed Aluminum section was 47 MPa and 127 MPa, respectively. The structural steel used in hollow SHS brace section had the average yield strength of 330 MPa. The average compressive strength of concrete cubes was found to be 36.2 MPa and 47 MPa at 28 days and 240 days (the day of testing), respectively. The typical average yield strength of TMT reinforcing bars of various diameters used in RC frame was about 522 MPa.

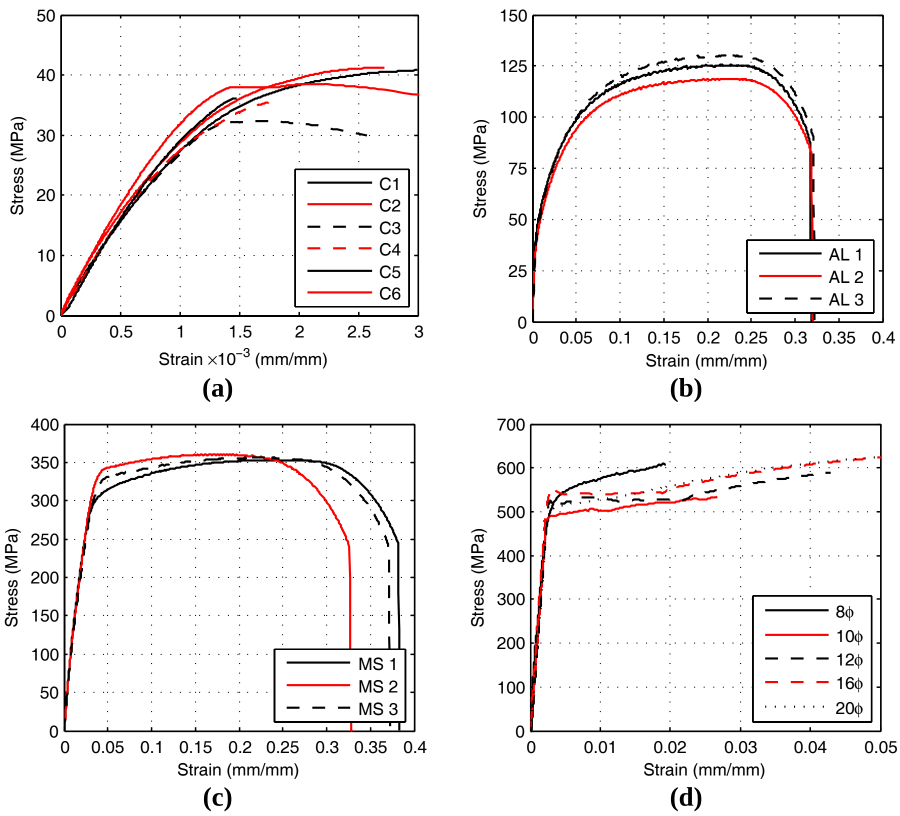


Figure 2.5 Stress-strain plots for (a) Concrete cylinder compression test at 240 days, (b) Tension test on Aluminum, (c) Tension test on Mild Steel and (d) Tension test on reinforcing steel bars

The general arrangement of the test setup is shown in Fig. 2.6a and reinforcement cage for various members of the test specimen are shown in Fig. 2.6b. A steel reaction frame having an estimated lateral force capacity of 4000 kN was used in the study. The servohydraulic controlled actuator (model MTS 243.70T) was used to apply lateral load to the test frame. The actuator was controlled using MTS FlexTest GT controller which had the capability of feedback in order to match the actuator actions and its commands precisely. The force from the actuator was distributed throughout the slab length using four ISMC 125 channel sections running the entire length of the slab. Lateral support to the test frame was provided in the form of a steel frame made of ISMB 500 column sections mounted with four cylindrical roller-bearings to keep the frame loaded in-plane and to prevent its out-of-plane movement. Confinement reinforcement was provided in column up to a length of 500 mm from the face of the joint and continued in to the joint as well. Both column and the beam had closely spaced shear reinforcement near the joints in the form of ties at the spacing of 100 mm over a length of 500 mm from the joint into the column and 800 mm from the joint into the beam.

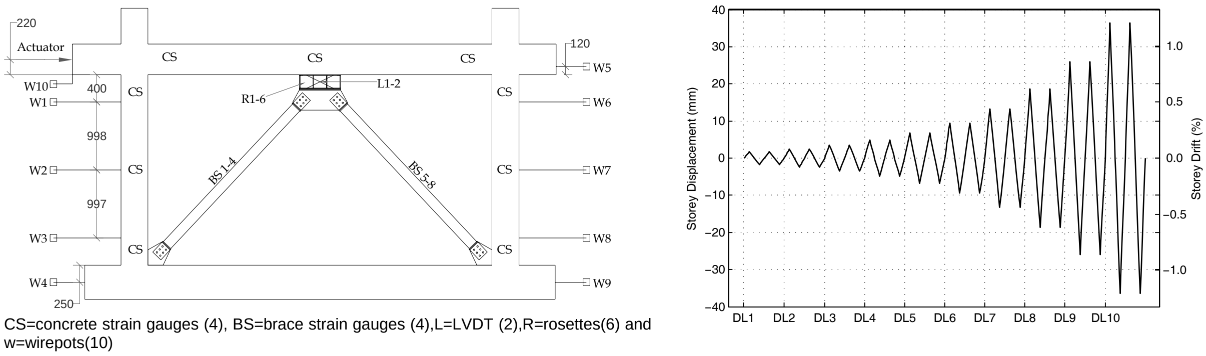
(a) (b)

Figure 2.6 (a) Test frame during concreting showing reaction and lateral support frames, (b) Reinforcement details of column (left), footing (top) and beam (bottom)

2.1. Instrumentation and Loading History

Several sensors in the form of electrical resistance strain gauges (ERSGs), linear variable differential transformers (LVDTs) and wire potentiometers (WP) were used in the test to monitor different parameters of the frame during the tests (Fig. 2.7a). The actuator was equipped with in-built displacement transducer and a load cell.

The ALSYD frame was tested according to the deformation loading testing protocol of FEMA 461 (2007). Past studies have showed that the ALSYD has a stable hysteretic behavior up to 20% shear strain (Jain, 2008). Accordingly, 20% shear strain was chosen to be the target shear deformation. Using 10 cycles of deformations, the initial target shear deformation was estimated as 1%. Each drift level of the shear link corresponds to particular storey drift of the frame in the ratio of the ALSYD depth and the storey height. Fig. 2.7b shows the slow cyclic displacement loading history for the ALSYD frame consisting of beam level displacements and associated drifts.



(a) (b)

Figure 2.7 (a) Location of sensors in the test frame and (b) Drift cycles of loading history used in the study

3. RESULTS & DISCUSSION

The testing program was conducted in three primary stages in which a total of two ALSYD units were used. The test with the ALSYD-1 unit was stopped at DL 8 due to a premature welding failure of brace end connection, which was subsequently repaired and the testing sequence was repeated, thus creating two phases of testing using ALSYD-1 unit. After removing the damaged ALSYD-1 unit, a new ALSYD unit (ALSYD-2) of same proportions was fitted in the test frame and was subjected to the same loading program. A summary of various components of the test setup and applied loading during the experiment is shown in Table 3.1. During each phase of testing, low amplitude-slow cyclic load-controlled tests were carried out on the ALSYD frames to evaluate the initial stiffness of the frames which were then followed by slow cyclic displacement-controlled tests. Fig. 3.1.shows the state of the test frame at the conclusion of the testing program with yielded and buckled ALSYD-2 unit.

Table 3.1 Various stages of the experimental program

No.	Test Reference	RC Frame	ALSYD	Loading	Remarks
1	ALSYD-1 (Phase I)	Original	ALSYD-1	DL 1 to DL 8	Damage to brace end connection
2	ALSYD-1 (Phase II)	Damaged from the Phase I loading	Damaged from Phase I loading	DL 1 to DL 11	Revised brace end connection
3	ALSYD-2	Damaged from both phases of ALSYD-1	ALSYD-2	DL 1 to DL 11	New unit of ALSYD replaced the damaged ALSYD-1.

Figure 3.1 Test frame at the conclusion of the testing program showing yielded and buckled ALSYD-2 unit and minor flexural cracking in frame members

3.1. Global Hysteretic Behavior

The overall hysteretic behavior of the ALSYD frames is characterized with stable and non-pinched hysteretic loops up to DL 10 as shown in Fig 3.2a & b. The peak lateral resistance achieved were 920 kN and 825 kN for the test frame with initial and replaced ALSYD units, respectively. No significant difference in the overall force-deformation behaviour was noticed in these two tests. The measurements of uniaxial strain gauges mounted on braces were used to compute brace axial forces. The braces remained elastic for all three tests and exhibited a peak force of 570 kN during the ALSYD-1 (Phase II) test as shown in Fig. 3.2c&d. The significant hysteresis of braces during the higher drift cycles was due to large plastic deformation of the yielded and buckled ALSYD units.

Envelope load-deformation response curves as well as global stiffness for each specimen at different stages of loading did not show any significant difference as shown in Fig. 3.3. The three tests have almost overlapping stiffness profiles throughout the loading history.

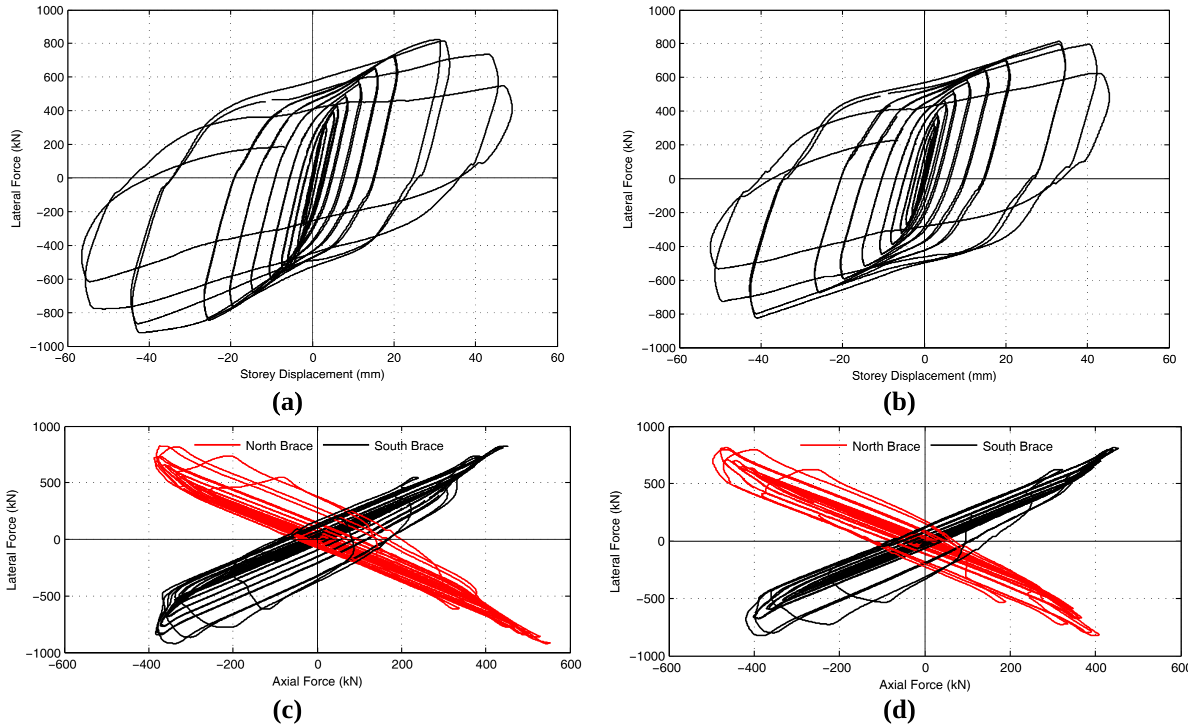


Figure 3.2 Overall hysteretic plot for (a) ALSYD-1 frame (Phase II) test (b) ALSYD-2 frame test and (c)-(d) Axial forces in braces during tests

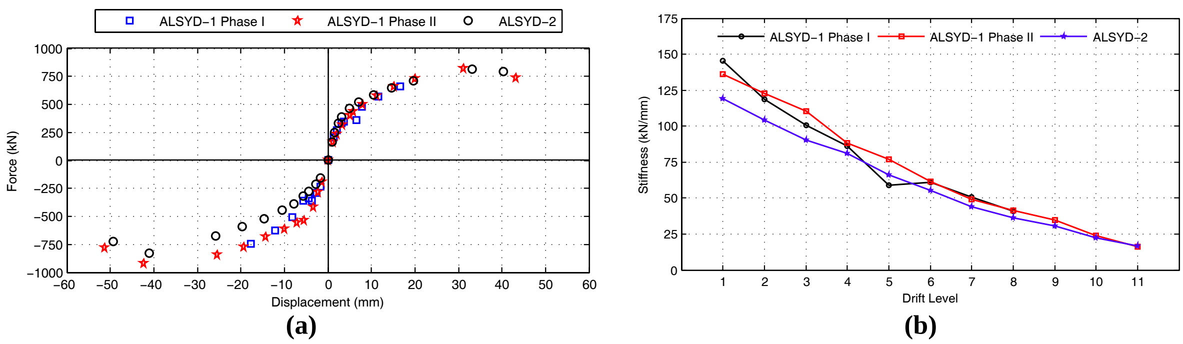
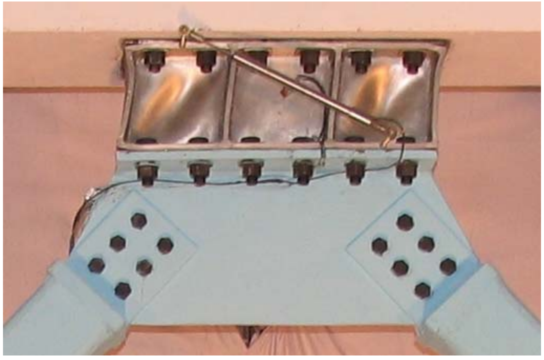


Figure 3.3 (a) Envelope load-deformation response and (b) Global stiffness of the ALSYD frames during tests

3.2. ALSYD Behavior

Hysteretic curves for the ALSYD units were obtained using shear strains computed from diagonal LVDTs mounted on the ALSYD and shear force obtained as the horizontal component of the brace forces. These curves are shown in Fig. 3.4 along with the deformed configurations of the ALSYD units. The ALSYD-1 unit underwent a peak shear strain of 7.7 % and experienced a peak force of 596 kN without any web buckling during the Phase I test. The ALSYD-1 (Phase II) and ALSYD-2 tests showed a similar behavior with the web buckling initiating during loading cycle of DL 9.The buckling became more prominent during DL 10 and eventually the web tearing was observed at DL 11. Both the later tests showed stable hysteretic loops up to DL 10 at which the web tearing reduced its resistance. The maximum average shear strains during later two phases were 18% and 19%, with corresponding shear stress of 82 and 84 MPa, respectively, indicating very good repeatability with different ALSYD units. The load sharing pattern of the ALSYD units and their contribution to overall energy dissipation and hysteretic damping is summarized in Fig. 3.5 during the three tests. From the Fig. 3.5a, it is evident that the ALSYD unit resisted in excess of 69% of the total lateral force applied to the frame.



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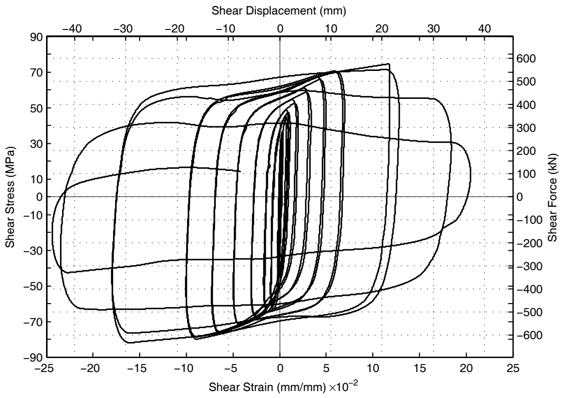

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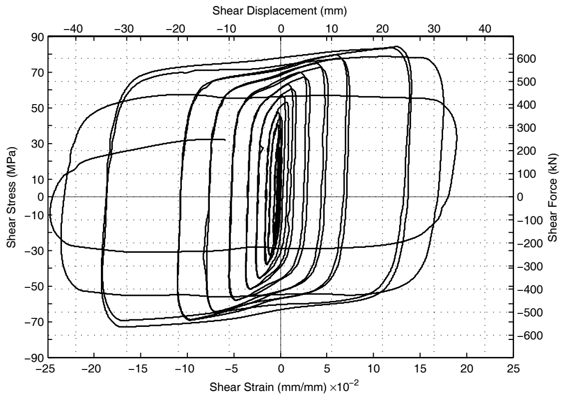
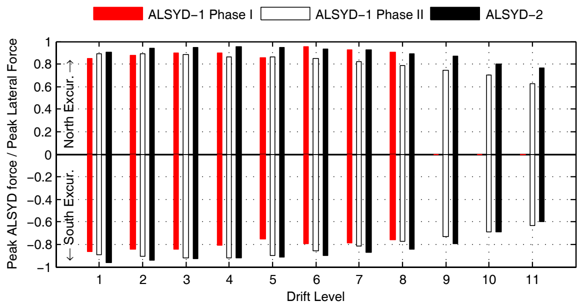


(d)

Figure3.4 Deformed configuration of (a) ALSYD-2 after DL 10 (b) ALSYD-2 after DL 11 and hysteretic behaviour of (c) ALSYD-1 (Phase II) and (d) ALSYD-2



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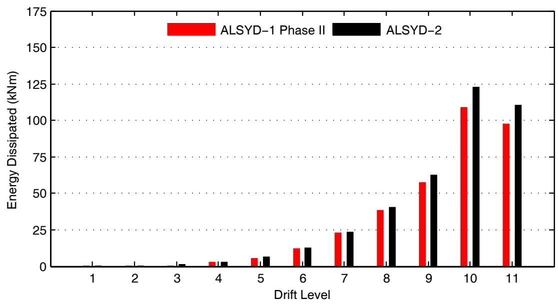

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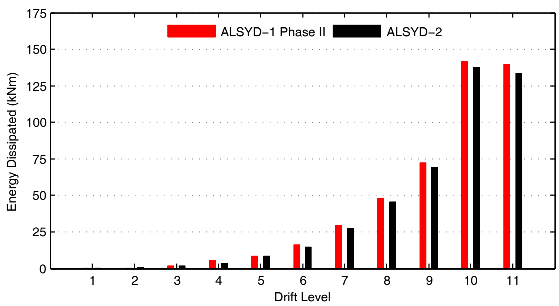

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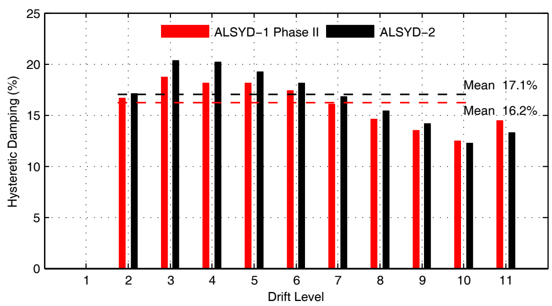

(d)

Figure 3.5 Comparison of (a) Force sharing by ALSYD (b) ALSYD Energy Dissipation (c) Global Energy Dissipation and (d) Hysteretic damping.

Energy dissipation by the ALSYD-1 (Phase II) and ALSYD-2 frames for each individual drift level is presented in Fig. 3.5b&c. Energy dissipation values steadily increased until DL 10. The ALSYD-1 (Phase II) and ALSYD-2 frames dissipated energies to the tune of 142 kNm and 137 kNm, respectively at DL 10. The respective energy dissipation by the ALSYD-1 and ALSYD-2 units was 109 kNm and 123 kNm. The amount of energy dissipation share of the ALSYD-1 was 77% while that for the ALSYD-2 unit was 90% for their respective frames. The hysteric damping values for ALSYD-2 frame are marginally higher than those for ALSYD-1 (Phase II) frame (Fig. 3.5d). The mean damping values for drift levels 2 through 10 were evaluated as 16.2% and 17.1% for the ALSYD-1 (Phase II) and ALSYD-2 frames, respectively.

3.3. RC Frame Behavior

The first appearance of cracking in the RC frame occurred during DL 8 in ALSYD-1 (Phase I) test. In case of the ALSYD-1 (Phase II) test new cracks appeared only during DL 10 and DL 11. No new cracks formed during the ALSYD-2 test and only the existing cracks from the previous tests continued to widen. The flexural cracks were present throughout the height of the column with their largest concentration at column ends followed by beam column joints and then the column mid sections as shown in Fig. 3.6. Beam ends showed a moderate amount of cracking. Moreover, various connections necessary to install ALSYD unit performed satisfactorily and were able to transfer loads without any sign of distress. Only exception has been the premature failure of brace end connection during the ALSYD-1 (Phase I) which after strengthening worked as expected during the last two test sequences: ALSYD-1 (Phase II) and ALSYD-2.

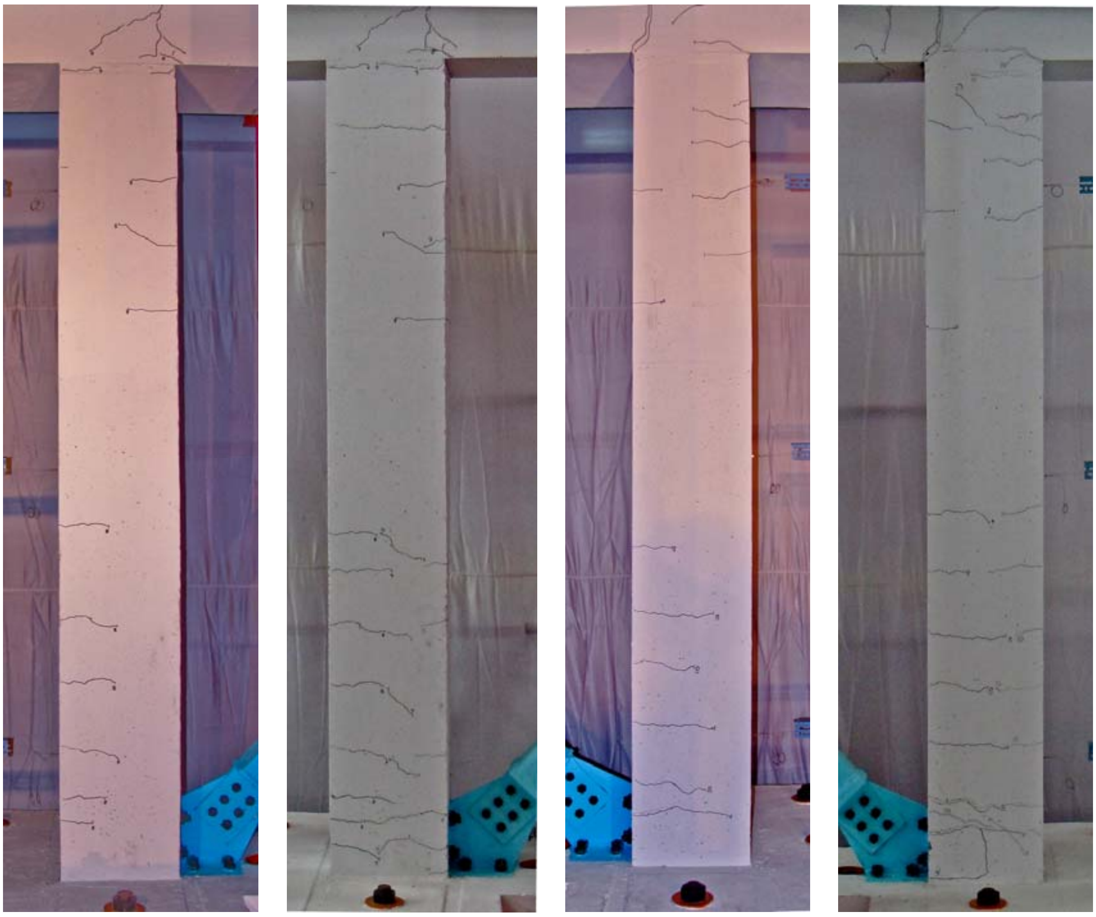

Figure 3.6 Comparison of cracking pattern in RC columns

4. CONCLUSIONS

RC frames fitted with ALSYD exhibited stable hysteretic response with no pinching and strength degradation. As expected, ALSYD units reached 18 to 19% of shear strain at storey drift of 1.2% accounting for 77 to 90% of the total hysteretic energy dissipated. The mean damping values due to hysteresis of ALSYD units were evaluated at about 16 %. Moreover, it was observed that the ALSYD units resisted in excess of 69% of the total load applied to the frame and, thereby, limiting the forces transferred to RC members and ensuing damage. All connection details worked satisfactorily permitting the full utilization of energy dissipation potential of ALSYD units. These experiments demonstrate that ALSYD units, as a device to enhance lateral stiffness and energy dissipation through hysteretic damping, can be used satisfactorily to upgrade the poor seismic resistance of OGS frames.

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