Seismic Response of Hybrid Buildings

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SUMMARY:
Based on materials and structural systems for load transfer, buildings may be classified as load bearing masonry structures, reinforced concrete (RC), steel frame structures and hybrid structures. Hybrid structures are those with two or more different lateral load-resisting systems. Hybrid buildings may be conceived at the design stage itself or could be the result of modifications or expansions in existing buildings. Mixed solutions are encountered when modern materials and structural systems are used in existing load bearing masonry structures. Often these are ad hoc, non-engineered solutions, without any structural design. Seismic response of hybrid structures differs from other structural systems as there is discontinuity, both in the lateral and vertical load transfer mechanisms. This study focuses on the seismic behaviour of such hybrid structures.

Keywords: Seismic vulnerability, hybrid buildings, mixed RC-masonry buildings, load-bearing masonry, RC

1. INTRODUCTION

Hybrid buildings can be defined as those structures that have two or more lateral load-resisting systems, either planned in the conceptual stage or as a result of modifications and/or expansions in existing buildings.

Seismic response of hybrid buildings is different from other structural systems as there is discontinuity, both in the lateral and vertical load transfer mechanisms. The response under lateral loads becomes complex due to explicit strength and stiffness discontinuities resulting from the use of different structural systems (e.g. junction of masonry shear walls and RC frame elements). The lateral load behaviour of masonry is different from that of reinforced concrete in terms of damage and failure mechanisms, energy dissipation and deformation capacity. Post–earthquake observations have revealed poor performance of RC and masonry hybrid structures and such structures are typically classified as a highly vulnerable class of buildings.

Very limited analytical and experimental studies have been conducted on the seismic response of hybrid structures. Information on lateral load behaviour of such structures through dynamic tests on reduced scale hybrid structures is available in the literature (e.g. Jurukovski et al., 1992, Modena et al., 1992). In recent years, researchers have explored the suitability of simplified macro-element modelling to perform non-linear analysis of hybrid structures (Cattari and Lagomarsino, 2006). There is a need to classify hybrid structures from a seismic vulnerability standpoint, investigate their seismic behaviour through various modelling approaches and lateral load experimental tests on assemblies, and to propose seismic strengthening or retrofit measures with a strong scientific basis. This paper addresses the aforementioned analytical and practical issues through an on-going case study.

2. HYBRID BUILDINGS

Often, hybrid or mixed solutions are encountered when construction economics play a paramount role, necessitating the use of modern materials and structural systems, such as RC, in an existing load-bearing masonry structure. A common practice in developing countries, such as India, is to provide RC columns with masonry to get open spaces (Bose et al., 2004). Hybrid structures as a class of existing buildings have been identified in other developing countries, such as Nepal (Bothara et al., 2000) and developed countries in Europe too (Modena et al., 1992, Lang and Bachmann, 2004 and Magenes, 2006). Very often these are ad-hoc, non-engineered solutions, without proper structural design or planning. The important link in these cases is that these building classes are encountered in seismically-prone regions of the world. Post earthquake observations have revealed poor performance of RC-masonry hybrid structures. Photographs of hybrid structures from the Kashmir earthquake in 2005 show extensive damage to masonry portions (see Fig. 1). The masonry portion appears to behave as the "fuse" due to its lower strength and deformation capacity. Hence, considering seismic vulnerability of hybrid buildings and the limited number of studies conducted so far, there is a need to address the seismic behavior of this class of buildings and develop appropriate retrofitting measures, as reiterated by researchers (Cattari and Lagomarsino, 2006; Magenes and Menon, 2009).

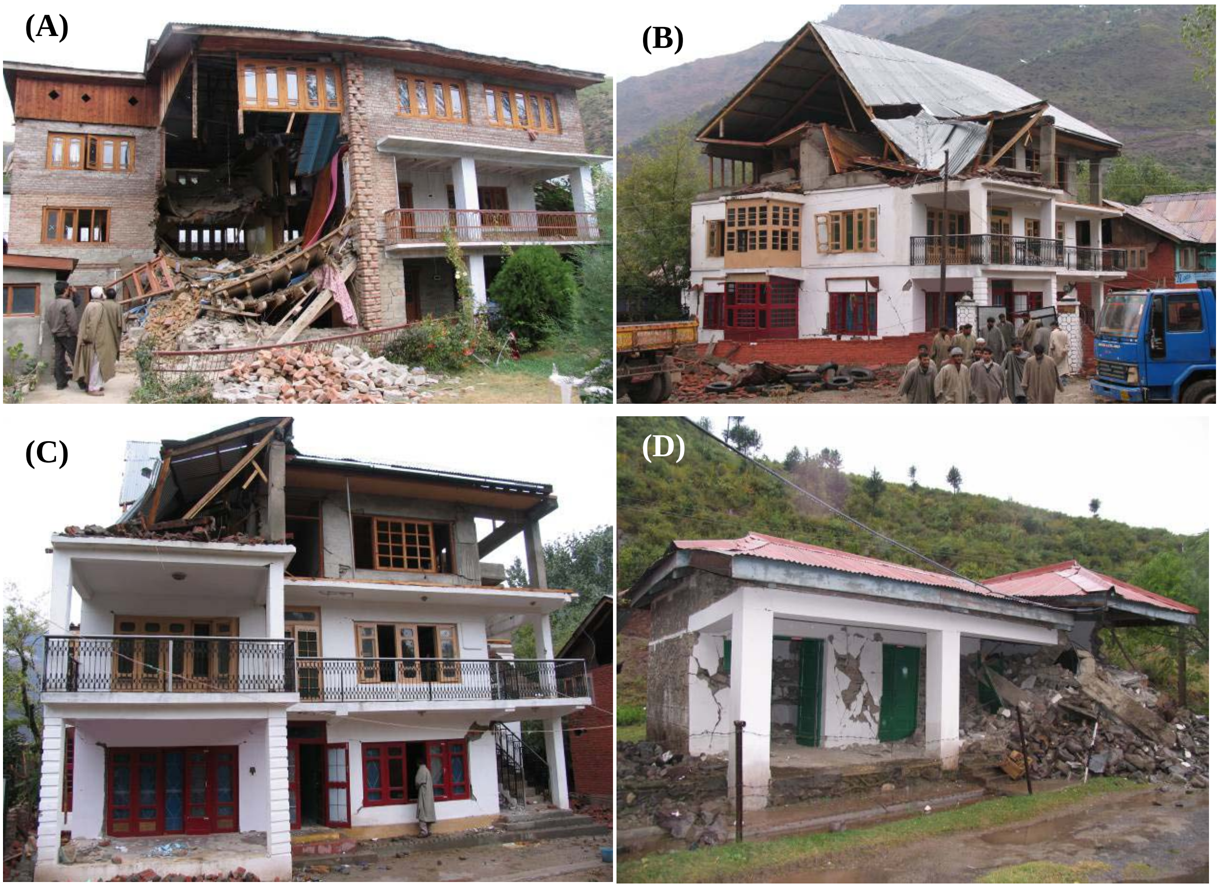

Figure 1. Damage observed in hybrid buildings in the Kashmir earthquake, 2005 (photo courtesy: CVR Murty)

Based on observations of constructions in India, an attempt has been made to classify hybrid buildings as follows (see Fig. 2):

a) Category A: Resulting from vertical expansion in an existing building (e.g. RC frame structure with masonry infill upon lower load-bearing masonry storey);
b) Category B: Resulting from horizontal expansion in an existing building (e.g. RC frame structure with masonry infill connected to structural masonry portions);
c) Category C: Load-bearing masonry structures, planned in the conceptual stage with shear walls, steel braces or other RC structural members;
d) Category D: Remodeled interior spaces in structural masonry with isolated RC elements.

The list is definitely not exhaustive. Jurukovski et al. (1992) report hybrid buildings with the ground storey in a mixed structural system (RC beams and columns, and brick masonry walls) and the remaining stories as classical brick masonry walls as a prevalent typology in Rimini, Italy.

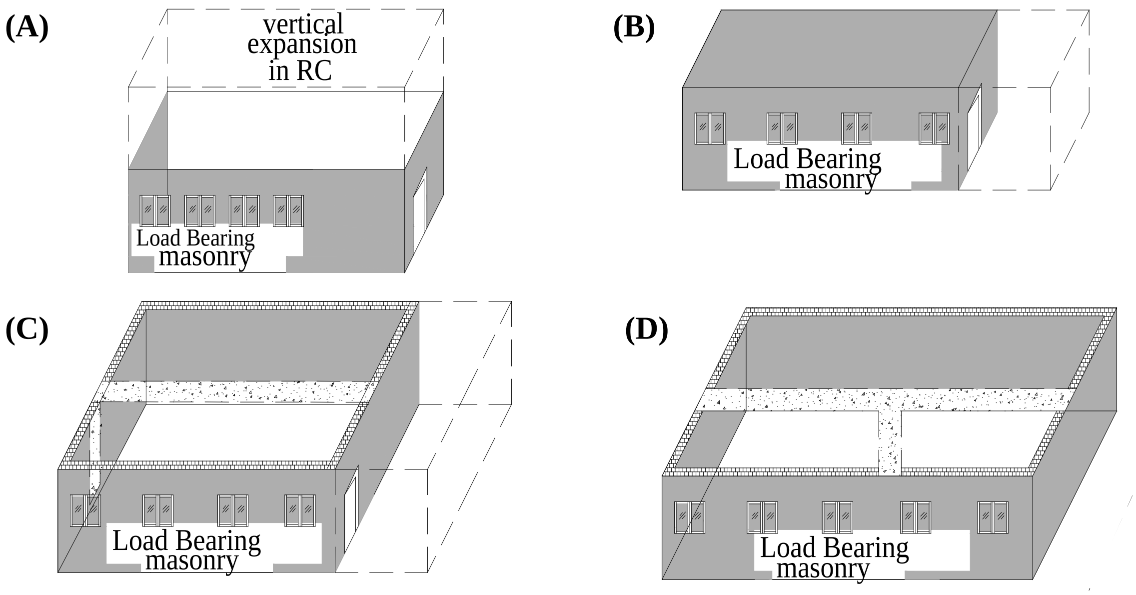

Figure 2. Categories A-D of hybrid buildings

3. STATE-OF-THE-ART OF RESEARCH

Limited number of experimental studies has been conducted in Europe, almost two decades ago, on mixed RC-masonry buildings. Jurukovski et al. (1992) conducted shake table tests on three 1/3-scale models of mixed buildings with basement constructed in a mixed structural system (RC beams, columns, and brick masonry walls), and upper three stories with classical brick masonry walls. Two different strengthening options, viz. introduction of RC core and RC jacketing to achieve framing action, were explored. Extensive damage to masonry walls in the ground floor of the original model was observed at a peak acceleration of 0.5g. Improved seismic safety was observed in both the strengthened models. Modena et al. (1992) conducted shake table tests on a 1:5-scale model of a three-storey prototype with peripheral reinforced masonry walls and internal RC columns, floor slabs with tie beams, aimed at calibrating theoretical models of global seismic behavior. While in-plane shear failure in the ground storey was noticed at a maximum intensity of 0.4g, good seismic response was notice, despite the small quantity of seismic resistant walls and small amount of reinforcement (0.4% horizontal reinforcement in masonry walls). Despite heavy damage to masonry walls in the ground storey, the load carrying capacity was not compromised (i.e. collapse was prevented).

The number of analytical or numerical studies on seismic behavior of hybrid buildings is also limited. Macro-element modeling to perform non-linear analysis of hybrid structures has been explored by past researchers (Valluzi et al., 2004, Cattari and Lagomarsino, 2006). Cattari and Lagomarsino (2006) studied two models of mixed structure: with external masonry walls and an internal RC column connected by beams to the structure, and a building with internal RC walls. In the former, masonry members progressively achieved their maximum resistance, and then RC elements that were still in the elastic range, increased the global resistance. In the latter, the converse happened: RC walls resisted the loads till collapse, and then the global resistance is increased by the masonry elements which do not achieve their maximum resistance.

Macro-elements are single or combined structural components of walls, floors or roofs with their mutual interactions considered in modeling. The stability of the macro-elements determines the ultimate capacity of the building. The in-plane behavior of masonry walls is represented by a frame type model by categorizing the wall into piers and lintels connected by rigid zones. The masonry panel’s behavior is characterized by reduced strength and stiffness in the non-linear phase. The simple element formulation minimizes computational load, and therefore 3D static non-linear monotonic procedures can be easily performed (Lagomarsino et al., 2006). The failure mechanisms considered are bending-axial force behavior, shear with bed joint sliding and diagonal cracking shear. However, this method does not provide much insight into the interaction between vertical displacement and rotation and bending-rocking mechanism. In modeling RC elements, an elastic-perfectly plastic behavior and concentrated plasticity for the ends of RC elements are considered. Shear and axial stress as brittle failure and axial-bending as ductile failure are the considered failure mechanisms.

Magenes and Penna (2009) recommend the use of non-linear static methods while modeling mixed masonry and RC buildings, given the dissimilar stiffness and deformation capacities. A simplified equivalent-static non-linear assessment method, based on the storey-mechanism approach is proposed. The storey-mechanism approach consists of separate non-linear shear-displacement analysis of each storey, where each masonry pier is characterized by an idealized non-linear shear-displacement curve (elastic-perfectly plastic, with limited ductility). Methods such as static linear and multi-modal response spectrum analyses assume that clear distinction between ductile and brittle failure mechanism is possible, which is not the case in masonry. In-plane response of masonry walls is typically governed by shear or shear-flexural failure modes and a moderate ductility has to be assigned in the analysis, which does not happen in static or modal spectrum analysis. While non-linear time history analysis is cumbersome for standard applications, non-linear static analysis or linear analysis with suitable response reduction factors is a good option. In non-linear static analysis, the performance acceptability is based on global target displacement at limit states, which refer to the overall state of the building. The state of every element is checked for shear force and drift demand against the ultimate capacity of the masonry elements. In a hybrid building where the main structural system is the masonry, structural checks on the elements may be made during the analysis.

Hence, other macro-element discretisation approaches, such as the non-linear equivalent frame modeling approach based on the consideration that the distribution of internal forces at the ultimate is governed by the strength of the members and their equilibrium (e.g. Magenes et al., 2006), is also appropriate for modeling hybrid buildings and performing non-linear static analysis.

4. SEISMIC ASSESSMENT OF A HYBRID BUILDING

4.1. Background

4.1.1. Building description

In order to study the seismic behavior of an RC-masonry hybrid building, a typical institutional building located in zone III of seismic hazard (maximum expected intensity VII, as per BIS 1893-1 (2002)) has been selected. This building was originally designed with two different load-resisting systems, RC columns and beams, and load bearing masonry wall, hence belonging to Category C. The structure selected for the study is Building Sciences Block (BSB), located in the Indian Institute of Technology Madras campus in South India. This building was constructed in 1961, consists of classrooms, labs and offices, and has a built up area of 11565 m^2, spread over three floors (see Fig. 4).

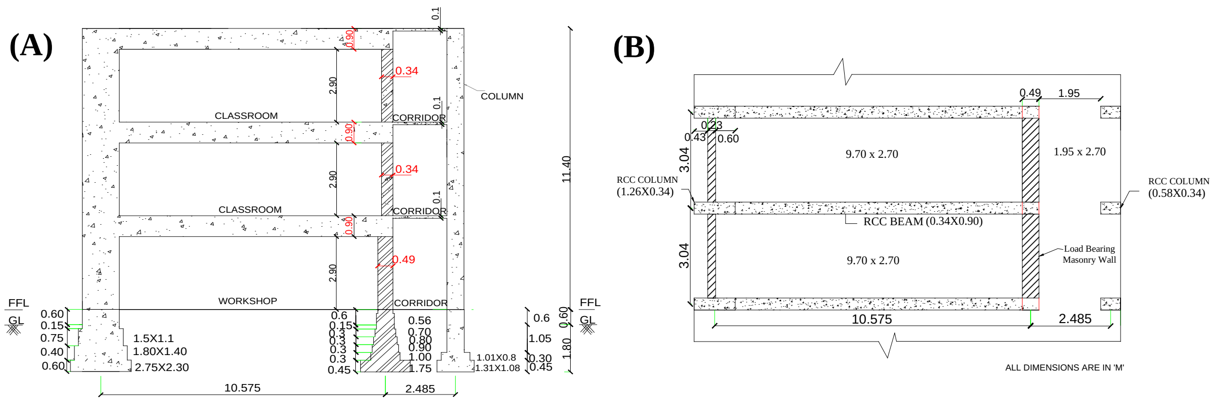

Figure 3. (A) Typical section through building; (B) Part plan at approximately +3.7 m level from ground level

BSB is H-shaped in plan with two long, parallel wings connected by a central wing. Both North and South wings typically consist of rows of class rooms (9.7m x 2.7m) with a connecting corridor 1.95 m width (Fig. 4F). The class room slabs (100mm thick) are supported on RC beams (0.34m x 0.9m in cross section), which in turn transfers loads at one end to an RC column (1.26m x0 34m in cross section) and at the other to a load bearing masonry wall (0.49m thick at ground floor, 0.34m thick on upper two floors). Refer to section and plan in Fig. 3 and photographs C-D-E in Fig. 4.

Figure 4. (A-B) Exterior views, (C-D-E) RC beam supported on masonry wall and RC column, F: Corridor

4.1.2. Materials

The materials used are unreinforced burnt clay brick masonry for the load bearing walls and M15 concrete for RC columns, beams and slabs. The secondary elements like the sunshades, fins and lintel beams are also in reinforced concrete. Grano flooring of 30 mm thickness is used in classrooms and in the corridors. A course of brick jelly lime concrete with an overlay of weathering tiles for a total thickness of 300 mm is provided over the terrace slab for heat insulation.

4.1.3. Loads

The loading considered are in accordance with BIS 875-1 and 875-2 (1987). The dead load consists of the weight of slabs, beams and the floor finish. The imposed load in the class rooms, corridors, and accessible terrace is 3.0, 4.0 and 1.5 kN/m^2, respectively.

4.2. Condition assessment

4.2.1. General

To assess the present condition of the building, a Rapid Visual Survey was conducted. The original construction drawings both architectural and structural were collected and studied. However, a detailed geometric survey was conducted to create as-built drawings by detailed physical measurements and compared with original drawings. Structural members were inspected by drilling to confirm sizes and materials used. The foundation soil was dug up at certain locations and it was found that the foundation details matched with the original working drawings. Original architectural and structural working drawings were retrieved from the firm that designed the building in 1959, M/s. Prynne Abbott and Davis (present-day M/s. Pithavadian and Partners, Chennai).

The general condition of the building is good without any signs of deterioration such as spalling of concrete, cracks in masonry or concrete, etc. However, as the building is 50 years old, non-destructive testing (NDT) to assess the strength and stiffness of the aged materials was decided upon. Data gathered thereby would be critical for proper structural modeling and analysis.

4.2.2. Non-destructive and partially destructive testing

To conduct a detailed NDT evaluation, various options have been explored. Ultrasonic pulse velocity test (UPV), Schmidt's rebound hammer test (RH) and core tests are to be conducted to assess the condition of RC members, while flat jack stress test and sonic tomography have been proposed for the load bearing masonry walls. The number of points of testing to be conducted for each test is decided based on limited in-situ testing recommended by CEN 1998-3 (2005) (see Table 4.1) as most of the original construction drawings are available and they are being verified with the actual construction (ground penetrating radar is being used to verify the presence and location of steel reinforcement). As per Eurocode-8 (EC-8), *limited in-situ testing is a procedure for complementing the information on material properties derived either from standards at the time of construction or from original design specifications or from original test reports* (CEN 1998-3, 2005).The above tests will provide an insight into the homogeneity, hardness and compressive strength of concrete and masonry. Durability tests to determine amount of carbonation, corrosion potential and chloride content in RC members would be performed.

Table 4.1. Recommended minimum for different levels of inspection and testing (CEN 1998-3, 2005)

	Inspection (of details)	**Testing (of materials)**
	For each type of primary element(beam, column, wall):	
Level of inspection and testing	**Percentage of elements that are checked for details**	**Material samples per floor**
Limited	20	1
Extended	50	2
Comprehensive	80	3

4.3. Proposed structural modelling and analysis approach

4.3.1. Knowledge level and admissible types of analysis

EC-8 has introduced a rational framework for assessment of existing buildings, highlighting the role of the knowledge level in a quantitative approach to assessment (Magenes and Menon, 2009). The code permits four main methods of analysis: viz. linear static (equivalent static or simplified modal), linear dynamic (multi-modal response spectrum analysis), non-linear static (pushover analysis) and non-linear dynamic (non-linear time-history analysis). Non-linear analysis is admissible only if the knowledge level is 2 or higher. In the current case, the geometry has been obtained from original construction drawings and full survey, while structural details have been obtained from incomplete original detailed construction drawings with limited in-situ inspection and material properties from original design specifications with limited in-situ testing, hence, satisfying the requirements of Knowledge Level 2. Structural evaluation based on this state of knowledge may be performed through either linear or nonlinear analysis methods, either static or dynamic (CEN 1998-3, 2005).

4.3.2. Modelling issues

There are various parameters to be considered in the modeling and analysis of a hybrid RC- masonry structure. A typical frame in an RC structure has connections made of the same material and therefore the load transfer mechanism is quite predictable. However, in a hybrid structure the connection is formed by two different materials, RC and brick masonry. Both have distinctively dissimilar strength and stiffness. The modeling of the joint connection formed by the masonry wall and the beam is the most critical as the behavior of this connection cannot be predicted. The cracking of a masonry wall with low or no tensile strength, together with the inelastic action of the joints between the wall and the slab, causes calculation complications not encountered in fully elastic frames (Sahlin, 1969).

The extent of moment distribution at the joint connection of the RC beam and masonry wall depends on the rigidity of the connection. The connection will not be rigid as the RC beam is supported on the masonry wall and the joint is formed by two materials of different strengths and stiffness. However, the joint will not allow full moment release. For reliable results, the extent of fixity assumed in the analysis should reflect the extent of fixity offered by the beam-wall joint, and hence is a very important modelling parameter. The behaviour of the masonry wall during seismic loading depends on the shear transferred from the RC beam to the wall. The extent of shear transfer depends on the joint rigidity. How the degree of fixity at the RC beam-wall joint can be determined and incorporated accurately in the modelling is a challenge of the current study.

4.3.3. Proposed methodology

As a first step towards understanding the behavior of the components in the structural system, a 2D model of a typical frame is analyzed. As the actual behavior of the joint is of partial fixity, the joint in the 2D frame is modeled and analyzed for two extreme cases of complete fixity and complete moment release under both gravity and lateral loads. A 3D analysis of a typical frame along with adjacent slabs will subsequently be investigated. A Finite Element model using solid elements for component level modelling will provide insight into behaviour of the RC beam-masonry wall joint. A global 3D model of the building between expansion-joints will be developed to understand the overall behavior of the building. 3D non-linear modeling will be performed using the macro-element discretisation approaches with equivalent frame modeling (Magenes et al., 2006, Lagomarsino et al., 2006). Non-linear static and dynamic analyses will be adopted for seismic assessment.

4.3.4. Analysis of a typical frame

A 2D frame (shown in Fig. 5) is modelled and analyzed in STAAD Pro V8i for two extreme boundary conditions at the RC beam-masonry wall joint: as a fixed joint and as a hinged joint. The force diagrams are shown in Fig. 5-6. The self-weight of the members is considered in the analysis. The moments and forces due to gravity loads and due to seismic forces (equivalent lateral forces) are considered and reported separately. The shear force transferred to the masonry wall in the case of a hinged end condition at the beam-wall joint is about 75%, for both gravity and lateral loading, compared to that for a fixed end condition, in the ground storey. Instead, the shear force transferred to the masonry wall in the case of a hinged end condition at the beam-wall joint is about 50%, for both gravity and lateral loading, compared to that for a fixed end condition, for the upper stories.

The actual stresses on the masonry wall at the beam-wall joint will be in between the stresses due to the assumed fixed or hinged end condition. It is proposed to determine the masonry stresses using flat jack testing and compare these stresses to an analytical estimate of the extent of load transferred from the RC beam to the wall.

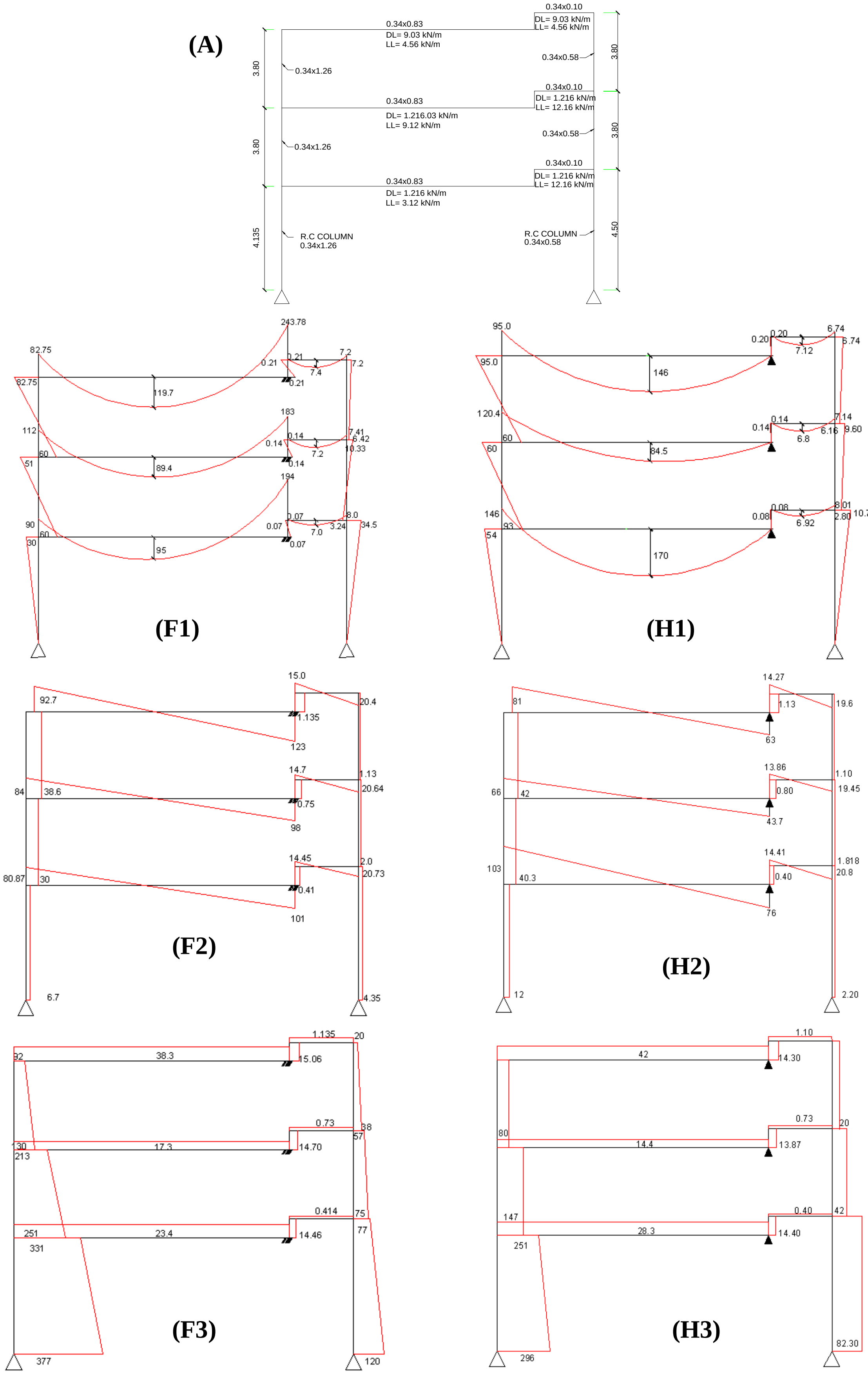

Figure 5. (A) Loading diagram, (F1-H1) Moments under gravity, (F2-H2) Shear forces under gravity load, (F3-H3) Axial forces under gravity load (Note: F-fixed, H-hinged)

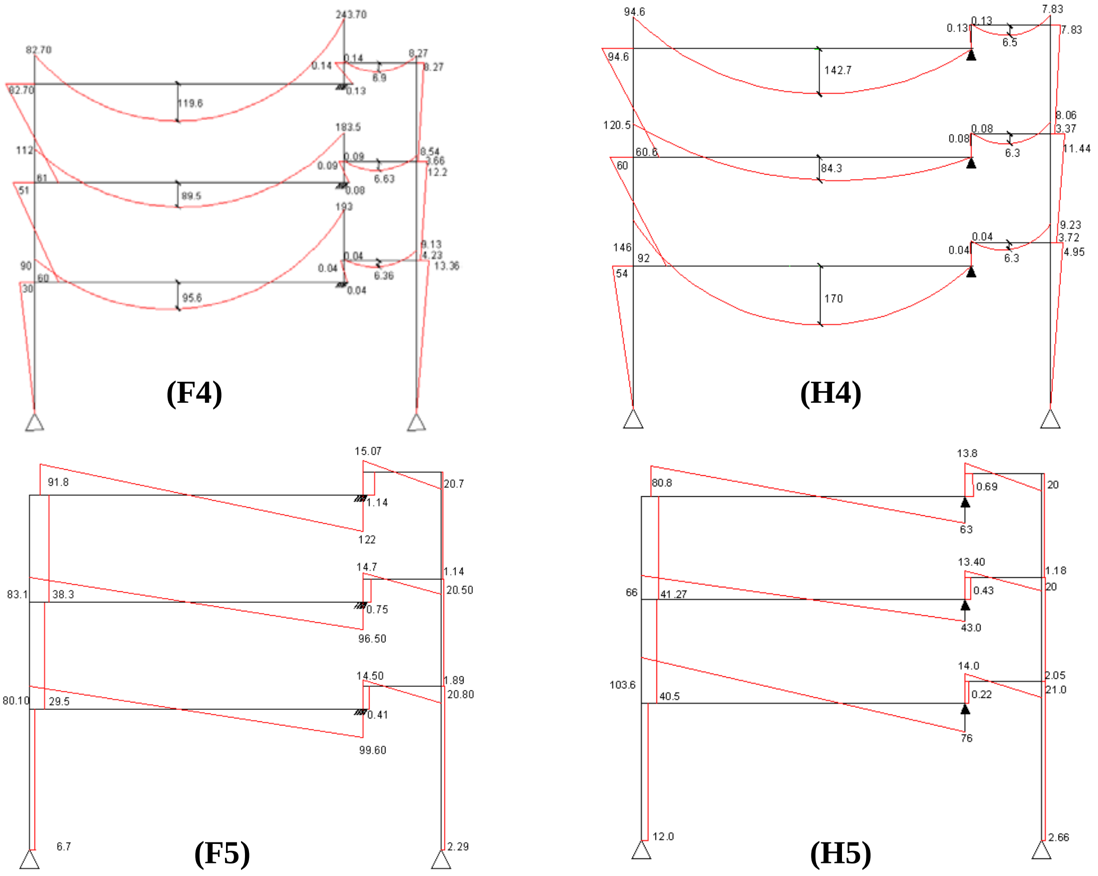

Figure 6. (F4-H4) Moments under lateral load, (F5-H5) Shear forces under lateral load

5. CONCLUDING REMARKS

The current paper addresses the issue of seismic response of hybrid RC-masonry structures, a class of buildings found in urban areas of developing and few developed countries. They typically represent poorly engineered or non-engineered structures and constitute a vulnerable class for seismic loading. A review of experimental and analytical studies on hybrid RC-masonry structures shows that the seismic vulnerability, assessment and retrofit of such structures have not been carried out within a structured framework. Initial efforts at addressing this lacuna are discussed in the paper. In particular:

- (a) A classification of hybrid RC-masonry in the Indian context has been attempted.
- (b) Crucial structural modeling issues, especially the difficulty in modeling connections between RC frame elements and the load bearing wall and the implications thereof, are highlighted.
- (c) A framework for retrieval of geometrical, structural and material data for modeling, within routine condition assessment of a chosen structure, to define the knowledge level and hence, the admissible analysis options, is explored.

The paper delves on the seismic behaviour a hybrid RC-masonry institutional building, originally designed with a hybrid load-resisting system, constructed in 1959-61. It would be of significance to understand if such a hybrid design was a prevalent structural solution, approximately 50 years ago in parts of Peninsular India, where it was not mandatory to design for seismic forces until 2002, when several regions in zone II were upgraded to zone III of seismic hazard (BIS 1983-1, 2002).

On a different note, traditional vernacular constructions in hilly seismic regions of India have always performed reasonably well during earthquakes (see Fig. 7). The buildings typically have foundations in random rubble masonry. Recent socio-economic pressures have led to non-engineered modifications in these constructions (e.g. use of RC retaining walls, RC columns). Construction of

Ekra houses with wooden frames and structurally designed RC foundations should be encouraged in the Himalayan regions, as it is a potentially safe model of hybrid construction in hilly regions. Proper studies are required to understand the behaviour of these modern hybrid Ekra and RC structures.

Figure 7. (A-B) Ekra houses, Sikkim from post-earthquake reconnaissance survey (18 September, 2011)

AKCNOWLEDGEMENT

The first author would like to thank IIT Madras for the opportunity to undergo the doctoral research program while employed as a staff.

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