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Seismic Performance of Precast Steel Reinforced Concrete Building

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Abstract: Precast Steel Reinforced Concrete (PSRC) structural frame systems for moment-resisting, comprised of Prefabricated Steel (S) girders and Precast Reinforced Cement Concrete (RCC) columns. This structural system has the advantage of inherent stiffness and damping during a seismic event. PSRC moment-resisting frame system is also known for its construction efficiency, lightweight and low-cost. Earlier investigations have shown PSRC systems useful in designing and constructing the buildings while maintaining ample strength and high ductility during seismic incidents. Despite much previous research on it, the use of the PSRC structural system in India is still limited. Previous studies have accepted a vital need to review thorough structural systems using experiment and analytical studies - to validate the understanding collected till date and act as evidence of concept for the PSRC moment-resisting frame system. This paper aims to facilitate more recognition and use of the PSRC structural system as a feasible choice to traditional RCC lateral resisting systems.

Two structures are studied to evaluate low-rise PSRC and RCC structures' performance during maximum considered earthquake events. These consist of typical steel beams and Precast R.C. columns frame buildings. Four-story PSRC buildings are designed according to Indian Codes of practice. Design columns under provisions of Indian reinforced concrete structures code, and beams are designed according to Indian steel construction code. The comparative studies for the two buildings are presented.

Keyword: Seismic Analysis, Pushover, PSRC system, RCC System, Moment resisting frame

Introduction

The modernization of steel and concrete structures provides attractive alternatives to reinforced concrete systems. PSRC structural systems for moment-resisting, comprises of Prefabricated Steel (S) girders and Precast Reinforced Cement Concrete (RCC) columns, have the advantage of the inherent stiffness and damping during a seismic event. PSRC moment-resisting frame system is also known for its construction efficiency, lightweight and low-cost. (Liang et al. 2004).

PSRC frame systems have been shown to retain numerous advantages from economic and construction viewpoints (Griffis 1986) compared to either RCC or steel frame systems. RCC columns are nearly ten times more efficient than steel columns in axial strength and axial stiffness (Sheikh et al. 1987). On the other hand, the deck slabs supported on steel girders are significantly lighter than the RCC beam-slab system, leading to significant reductions in the total building's load, costs of the foundation, and earthquake forces. In the previous years, the PSRC structural systems for moment-resisting have mostly been used for buildings located in low seismicity areas in developed countries. In most recent years, the researcher attempts to develop seismic design guidelines for PSRC systems located in high seismic risk regions (Liang et al. 2004).

Many researchers have developed testing models of PSRC frames based on a typical theme building devised for the US-Japan program (Mehanny 2000, Bugeja 1999, Noguchi 1998). These studies apply the suggested seismic design specifications for PSRC systems and then assess the seismic performance of resulting designs using nonlinear analyses and advanced performance assessment techniques. Traditional steel frames were also investigated in these studies to benchmark conventional structures' performance compared to the Precast SRC frames. Using a standard floor plan, the building heights varied and the implementation of perimeter versus space frame systems. These design studies have shown that the steel beam sizes tend to be similar for the PSRC and steel system and that the main disagreements lie in the RCC column and steel girders connection. Given the additional stiffness provided by the RCC columns, the SRC frames tended to be controlled more by the bare minimum strength requirements, whereas lateral drift limitations restricted the steel frames. In general, these studies have shown that the inelastic dynamic response of the PSRC frames is similar to comparably designed steel moment frames.

Cordova et al. 2005 design and test a full-scale 3-story SRC moment frame. Using the pseudo-dynamic loading technique, this specimen is subjected to a sequence of earthquake motions ranging in hazards from frequent to sporadic events. Using the results of the test specimens and recommendation, trial designs of three case study buildings (3, 6, and 20-stories) are generated, analytically modeled, and subjected to a collection of earthquake ground motions at a range of hazard levels. They Investigate differences between the response of beam-column subassembly and full-scale system testing and evaluate how this affects the interpretations from these tests.

One of the efficient tools of addressing the behavior of building under earthquake loading is pushover analysis. Due to its lack of sophistication, nonlinear static procedure or pushover analysis are used by the many structural engineers. When pushover analysis is used carefully, it is widely accepted that it provides valuable data that cannot be achieved by linear static or dynamic analysis procedure (Mehmet inel et al. (, 2006). This paper intends to study the seismic performance of the PSRC system for buildings compared to ordinary RCC buildings.

Pushover Analysis

The structures deform inelastically during the maximum considered earthquake (MCE). Hence structural performance must be checked during the post-elastic behavior of the structure. Static nonlinear analysis (also called Pushover Analysis) should be used to evaluate seismic performance because the elastic analysis can not determine the structure's post-elastic behavior during such events. Moreover, to estimate the seismically induced needs that exhibit inelastic behavior, the structures' maximum inelastic displacement requirement should be determined effectively.

In the static nonlinear analysis method, the monotonically increasing horizontal loads are applied to the structure with invariant distribution over the height until the top story displacement reaches the target displacement value. In this analysis method, the superposition principle is used to get an approximate force-displacement curve of the structure by adding the response of a successive series of elastic analyses. The nonlinear static gravity loads are applied initially, and all horizontal force-resisting elements are formed as 2-D or 3-D structures with bilinear load-deformation graphs.

A predefined horizontal load distributed along the building height is applied. The horizontal loads are increased until some elements yield. The structural model is revised to account for the reduced stiffness of yielded elements due to formation of hinges, and horizontal loads are again increased until additional elements yield. The procedure is continued until a observed displacement at the top of the building gets a required deformation level, or the structure turn out to be unstable. The top roof horizontal displacement is mapped with base shear to get the capacity graph (Fig 1).

Nonlinear static analysis efficient for capturing strength and stiffness degradation in structural elements due to large deformations caused by horizontal loads. A substantial computational challenge is to precisely arrest the negative post-peak response. Such response leads to the need for robust iterative numerical solution approaches to minimize errors. SAP2000 software can overcome this issue negative post-peak by investigate the sensitivity of the solution [FEMA P695].

Seismic Performance of Buildings

The state of damage measures buildings' seismic performance under a specific seismic hazard level. The form of damage is measured by the roof's displacement and the structural elements' displacement. Primarily, gravity nonlinear analysis is carried out using the force control method. It is followed by a lateral load with displacement control using SAP2000.

To perform displacement-based nonlinear static analysis, target displacement needs to be defined. This gives an understanding into the highest base shear that the structure can withstand. The building performance depends on the structure elements performance levels and the nonstructural elements. A performance level depicts a limiting damage requirement, which may be deemed acceptable for a given building with specific ground motion. The performance of the structure is determined by hinges formation in structural elements. Different types of plastic hinges like uncoupled/coupled moment, torsion, axial force, and shear hinges are available in standard analysis program. After yielding of the structural elements, plastic hinges will form at predefined locations, indicating the risk level (Fig. 2 and Fig. 3). The performance point is calculated from the guideline defined in FEMA-356 and ATC-40. The horizontal load is applied at the deformed state of the general loading from point A (Fig. 2). No hinges will be formed before point B, where the structure will show linear behavior, and after that, one or more hinges will start to form. The software will show hinges with the following remarkable indication:

Immediate occupancy I.O.: indicates the state of damage in which limited nonstructural damage has occurred. The structural elements of the building maintain their original strength and stiffness. The probability of life-threatening injury is very low because of nonstructural damages, and minor repairs of these nonstructural elements can be repaired before reaccompancy. [FEMA-356].

Life safety level L.S.: indicates state of damage in which substantial damage to the structural elements has occurred, but some scope against either partial or total structural collapse persists. Many structural elements are severely damaged, but this has not resulted in large falling debris hazards. Injuries may arise during the at this stage; however, the overall probability of life-threatening injury is low because of low structural damage is expected and it is feasible to repair the structure [FEMA-356].

Collapse prevention CP: indicates the state of damage in which the building is on the limit of partial or total collapse. Significant damage to the structure has occurred, possibly including significant degradation in the stiffness and strength of structural elements, permanent lateral deformation of the structure, and degradation in axial stiffness and strength. Substantial threat of injury may happen due to collapsing of structural debris. The structure may not be practical to repair and is not safe for reoccupancy. [FEMA-356].

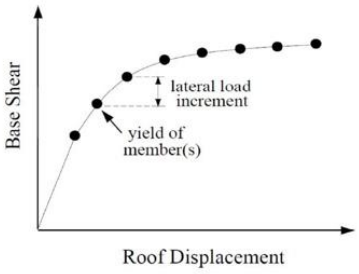

Fig.1 Expected Capacity Curve of the frame element.

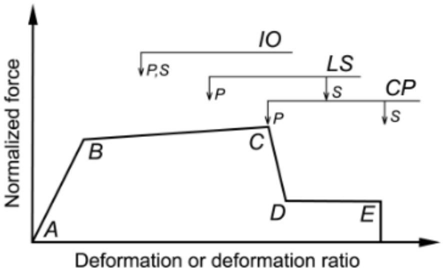

Fig.2 Generalized Component Force-Deformation Relations for Depicting Modeling and Acceptance Criteria [FEMA-356].

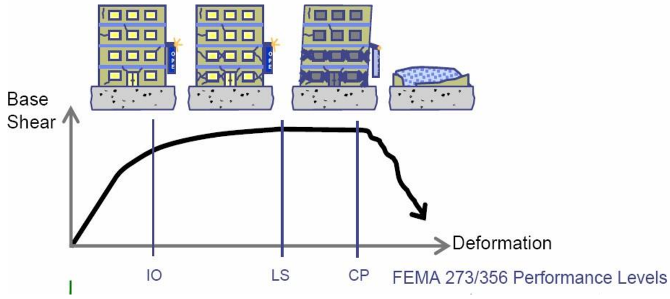

Fig.3 FEMA 273/356 Performance levels (taken from Fajfar et al. 2004)

Description of Studied Structures

Two structures are considered to represent low-and medium-rise PSRC and RCC structures to study. These consist of a typical steel beam and Precast R.C. columns frame building. Four-story PSRC buildings are designed according to Indian Codes of practice. Design columns under provisions of Indian reinforced concrete structures code, and beams are designed according to Indian steel construction code.

The longitudinal and transverse bars' yield strength for RCC beams and columns used as 500N/mm^2. The compressive strength of concrete used was 25 MPa at 28 days. The structural steel had a yield strength of 250N/mm^2 used in the analysis.

The column center to center dimensions was 5000 mm in both directions. The model is assumed to be pinned at the base. The column and beam details have been done as per the Indian Code of Practice. The 300mm wide and 400mm deep beam with 3 bars of 16mm diameter at top and bottom were used at all levels and in both directions, plus an extra 2T16 at the support. The 400mm x400mm columns with 8 bars of 20mm diameter and 8mm diameter wire were used as stirrup at 100mm c/c near the beam-column junction and 150mm c/c near the mid-height of the column. The story height was kept as 3000mm c/c of the beam on all floors. For PSRC structural system, steel girders of ISM300 are considered.

Building Performance

The lateral load pattern for zone IV corresponding to the Indian Earthquake Loading Code (IS1893-2016) is implemented and applied in SAP 2000 as auto lateral load pattern. The lateral load pattern is computed considering full dead load and 25% of live load for calculation of lateral loads. The direction of checking the building's behavior is the same as the lateral load direction. PM2M3 type hinges are assigned to columns and M3 type hinges are assigned to beams.

RCC and PSRC buildings were analyzed using the SAP2000 program. Base columns are assumed hinged at the foundation level. The beams and columns are modeled as nonlinear frame elements with lumped plasticity; hinges are defined according to the section properties at both ends at the columns and beams.

The pushover curve for the PSRC building is shown in Fig. 4 and for the RCC building in Fig 5. The pushover curves with each associated response spectrum curve for different levels of shaking levels are shown in Fig 6 for PSRC structures and in Fig 7 for RCC structure. The hinge patterns are shown in Fig 8 for the RCC structure and in Fig 9 for the PSRC structure.

In the RCC building, plastic hinges formation starts with beam ends then propagates to the beams of the second level. After that point, intermediate base columns of lower levels then propagate to the intermediate columns of the second level; the plastic hinges are performed at the lower level's outer columns and carry on with yielding of interior columns in the upper levels until collapse occurs.

In PSRC building, plastic hinges formation starts with intermediate columns of the lower level, then propagates to interior columns in the upper levels and the intermediate columns of the lower level reaching collapse before the outer columns, then a failure mechanism occurs as the soft story of the lower level.

Conclusions and Summary

A viable nonlinear finite element program (SAP2000) was used to examine the static nonlinear behavior (using pushover analysis) of (PSRC) structures for horizontal seismic loads. Two buildings are modeled to represent low-rise structures in seismic zone IV. A comparison with ordinary RCC buildings is presented. The results show that even both structures have almost the base shear capacity, the PSRC structures behave linearly till the maximum shear base capacity is reached and the soft story failure mechanism occurs.

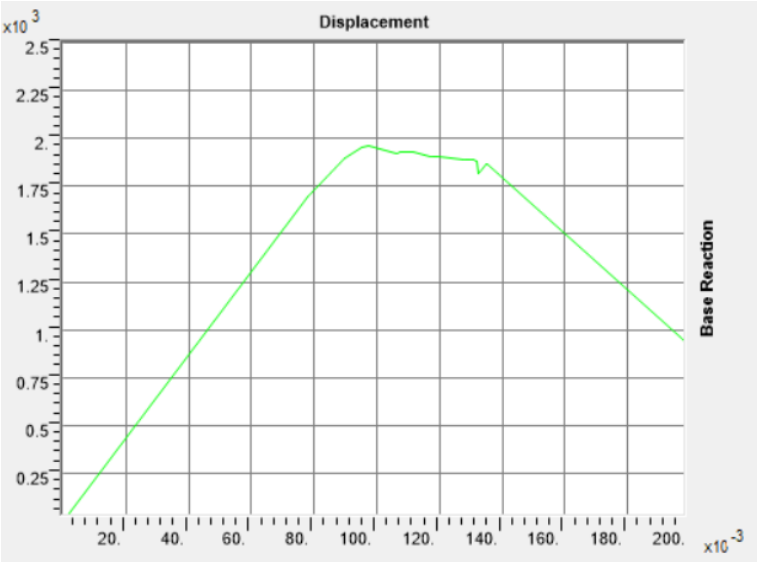

Fig. 4 displacement vs. base shear for PSRC structure

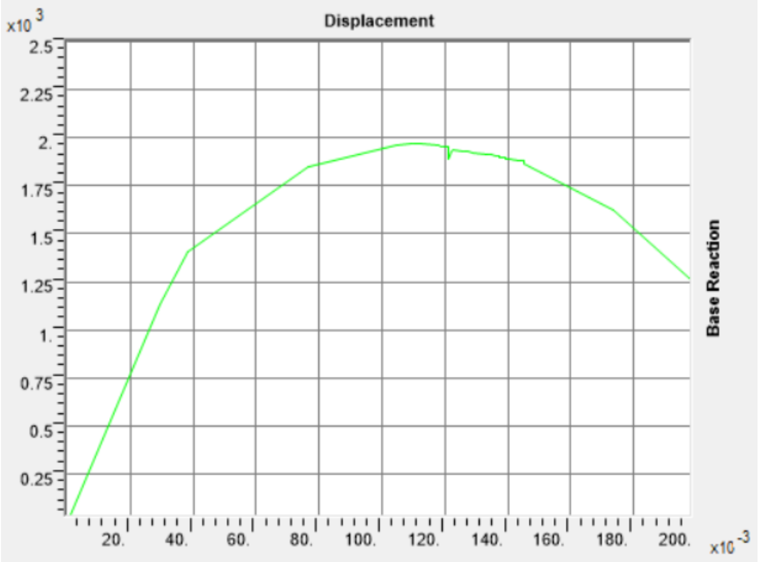

Fig. 5 displacement vs. base shear for RCC structure

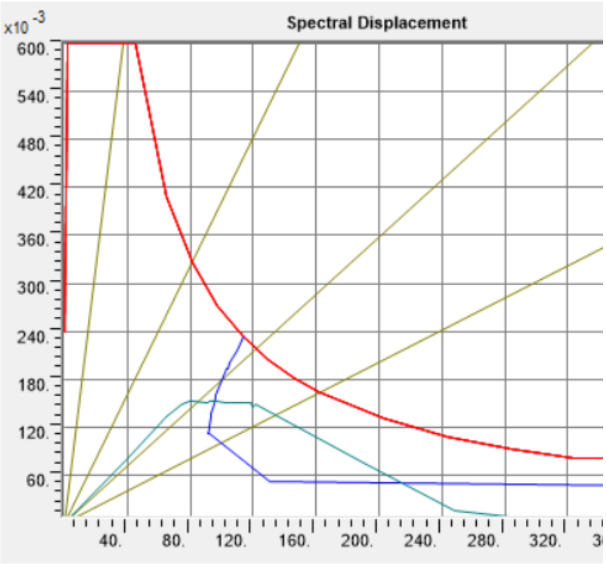

Fig. 6 pushover and demand spectrum for PSRC building

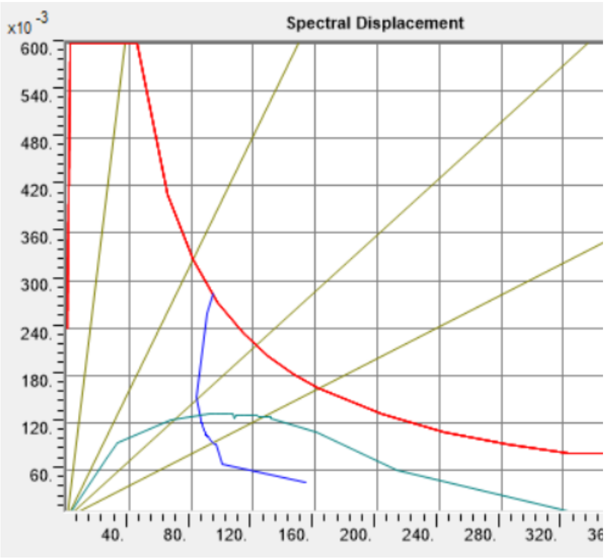

Fig.7 Pushover and demand spectrum for RCC building

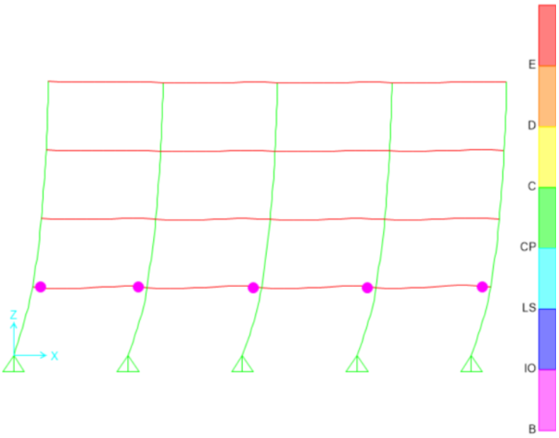

Fig8-a Plastic hinges in the RCC building start at beams of the lower floor.

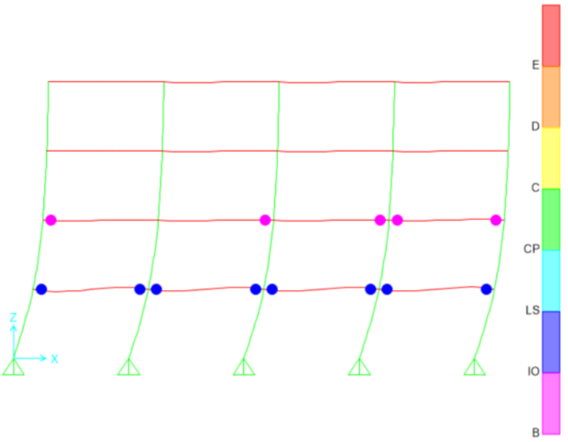

Fig8-b Plastic hinges in RCC building propagates to the at beams upper story.

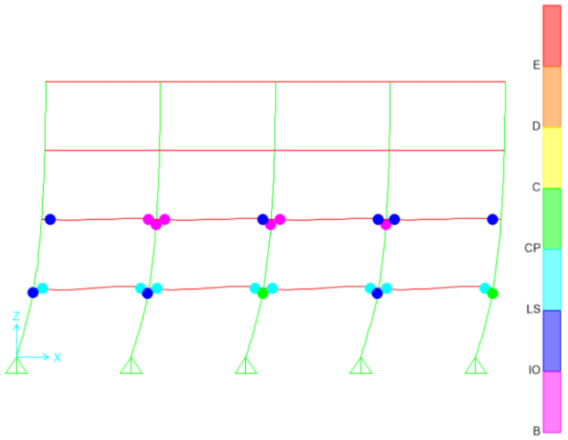

Fig8-c Plastic hinges in RCC building propagates to the intermediate & Exterior column.

Fig. 8 Hinge pattern for R.C. building.

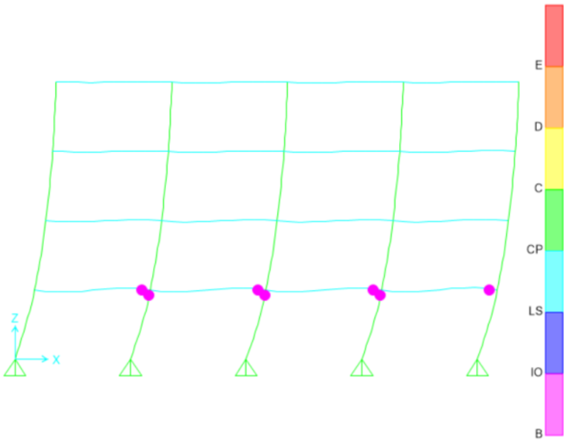

Fig9-a Plastic hinges in PSRC building starts at intermediate columns of the lower story.

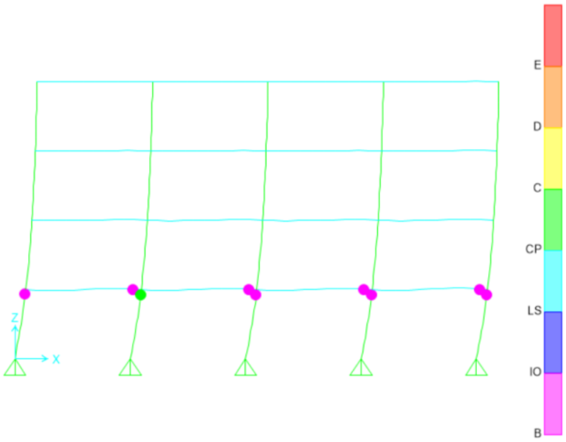

Fig9-b Plastic hinges in the PSRC building propagate to the lower story's outer columns.

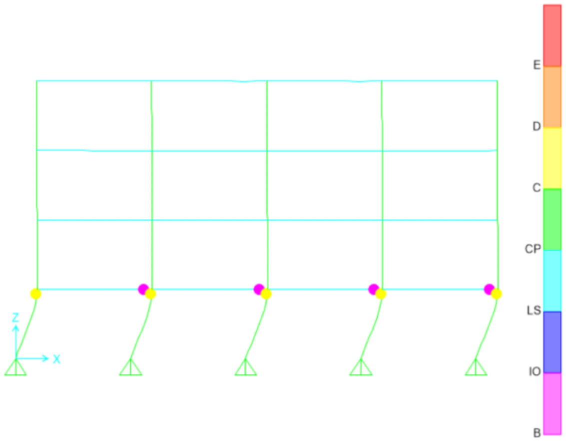

Fig9-c plastic hinges in PSRC building at failure.

Fig. 9 hinge pattern for PSRC building.

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