A Critical Review on Seismic Performance and Vulnerability Assessment of Vertically Irregular Buildings

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***Abstract*—Soft story buildings exhibit significant vulnerability under seismic loading due to uneven stiffness distribution, resulting in the concentration of seismic demand and localized failure. Previous studies consistently emphasize the critical effects of stiffness irregularities, soft story mechanisms, and material configuration on overall building performance. Findings reveal that buildings with Properly designed infills and bracing systems significantly improve seismic resistance by enhancing lateral stiffness and controlling story drift. Comparative analysis between SMRF and OMRF frames demonstrates that SMRFs offer higher displacement capacity and improved collapse prevention. Experimental and analytical models further confirm that infilled frames enhance lateral strength and energy dissipation, though weak masonry may induce undesirable shear failures in columns. Moreover, the seismic q-factor and ductility assessments underline that frame height and local ductility substantially influence structural performance. Altogether, the reviewed studies establish that a comprehensive approach integrating stiffness modification, improved column design, and performance-based evaluation is essential to mitigate soft story vulnerabilities in RC frames.**

***Index Terms*—infill wall, soft storey, vertical irregularity, seismic vulnerability, pushover analysis.**

I. INTRODUCTION

Earthquakes are considered to be one of the most unpredictable and devastating natural hazards. Earthquakes pose multiple hazards to a community, potentially inflicting large economic, property, and population loss. One of the measures used in order to combat or reduce the devastating effects of earthquakes is through the seismic risk assessment of existing buildings.

Several procedures have been developed in order to allow communities to prevent and mitigate losses in the event of an earthquake. One such technique is assessing existing buildings to determine which buildings are safer if an earthquake is to occur. However, the number of structures is too large and would take a significant amount of time and resources to be assessed in detail. A preliminary assessment is then introduced in order to determine which buildings should be prioritized for a detailed assessment. One such tool is the American tool FEMA154 by the Applied Technology Council and Federal Emergency Management Agency (ATC 2002). It should be emphasized that preliminary assessment procedures are merely tools for prioritization and cannot actually determine if a building is definitely safe from earthquakes. Seismic performance evaluation is based upon individual deformation capacity of an element as well as overall structural deformation capacity. Conventional seismic design in codes of practice is entirely force-based, with a final check on structural displacements. Seismic design follows the same procedure, except for the fact that inelastic deformations may be utilized to absorb certain levels of energy leading to reduction in the forces for which structures are designed. This leads to the creation of for over-strength, energy absorption and dissipation as well as structural capacity to redistribute forces from inelastic highly stressed regions to other less stressed locations in the structure and effects not explicitly considered in code applications. Although the code requires special ductile detailing, it does not provide a means to determine how the structure will perform under severe earthquake conditions. This paper highlights a procedure for evaluating the behavior of a structure and its response when subjected to seismic forces. Following terms are briefly defined to understand their implication on the seismic performance.

II. REVIEW OF LITERATURE

To provide a detailed review of the literature related to assess the seismic performance of reinforced concrete frame vertical irregular buildings of the structures and their vulnerability study in its entirety would be difficult to address in this paper. A brief review of previous studies seismic performance evaluation of structures is presented is this section. This literature review focuses on evaluation of seismic performance of structures and past efforts most closely related to the needs of the present work.

Adrian Fredrick C. Dya., Andres Winston C. Oreta (2015) observed that the main cause for soft story buildings to be more susceptible to earthquakes is the localization of seismic forces. Though the total demand on the building is smaller due to the increased height, uneven demands on the areas of the building results to a local hazard. The forces are concentrated on the segment of the building where there is a reduction in stiffness which is at the location of the soft story. This can be observed through the development of the plastic hinges, the story drift of the buildings, as well as the design. These seismic parameters show a localization of seismic demand. The risk of the building is increased due to the increased hazards of specific areas. The increase in risk is also dependent on the amount or the severity of soft story of the building and thus the soft story irregularity modifier is further categorized to consider its severity. It is recognized that any building that is designed properly will be able to withstand seismic excitation without incurring considerable damage. Building structural designers should take careful note of this area when designing soft story buildings.

A. Cinitha.A, P.K. Umesha, Nagesh R. Iyer (2012) observed that the capacity against demand is significantly higher for SMRF building frames compared to OMRF. The user-defined hinges takes into account the orientation and axial load level of the columns compared to the default hinge. The study reveals that plastic hinge length has considerable effects on the displacement capacity of frames. Based on the analysis results it is observed that inelastic displacement of the modern code-conforming building frames is within collapse prevention level. From the study it is apparent that, the OMRF framed buildings are more vulnerable than SMRF. The vulnerability index of the building quantitatively expresses the vulnerability of the building as such, whereas storey vulnerability index assists to locate the columns in the particular storey in which significant, slight or moderate level of damages have taken place.

Danish Khan, Aruna Rawat (2016): In the study, eccentric bracings were used as a means to reduce soft storey effect in masonry infill reinforced concrete (RC) building. Masonry infill RC soft storey buildings with first storey free of infill is generally a preferred configuration of multistorey buildings in India. Due to lack of stiffness in first storey, these building undergo large displacements at first storey level and hence are highly vulnerable under seismic loads. The results clearly show that large displacements occur at first storey level in soft storey building compared to other type of buildings i.e. bare frame and infill frame. It is also observed that large portion of displacement concentrates in first storey and hence other storeys are undamaged.

An economical scheme of strengthening is proposed which consists of steel eccentric bracings placed at first storey which results in increased stiffness of that storey. In practice, the bracings will act as fuse during earthquakes enduring most damage while keeping the building undamaged. It is observed that increasing moment of inertia does not have proportionate effect on storey drift. Also, the eccentricity distance has some effect on drift and it is recommended to connect the bracings at middle of beams, if possible. Further, fragility curves for soft storey frames with bracings show that probability of collapse is reduced in comparison to soft storey frames.

Syed Humayun Basha, Hemant B. Kaushik (2016)
Studied the behaviour of eleven half-scale, single-story masonry infilled reinforced concrete (RC) frames under slow cyclic in-plane lateral loading experimentally in two stages. Results obtained in the first stage (eight frames) showed that the frames infilled with full-scale and half-scale bricks exhibited higher strength, stiffness, and energy dissipation than

their bare frame counterparts. In most cases, columns failed in shear even though the masonry used was quite weak. In order to delay the shear failure in columns, shear design of columns was enhanced as per the existing earthquake standards, and tests were repeated on three improved frames in the second stage. Though shear failure in columns of the improved frames occurred at higher drift level, the shear failure in columns could not be prevented showing the inadequacy of current design codes. Based on the experimental results, an idealized load–displacement relationship for masonry infilled RC frames was developed for different performance levels. This may serve as a guideline in the design of similar infilled frames for required performance levels. It is important to note that due care has to be taken while designing RC frames infilled with weak masonry, as they may also alter the failure mechanism of RC frame system.

Romanbabu M. Oinam, Ruban Sugumar, Dipti Ranjan Sahoo (2017) investigated three geometrically similar frames, having different configurations of masonry infills. The first frame was a bare frame, the second fully infilled frame and the last one open ground storey frame. The frames were modelled in OpenSees simulation platform, utilising material and section properties available in its library. Their work mainly focused on studying the effect of masonry infills in the RC frames and its hysteretic response during an earthquake event, where it was expected to go into the non-linear range. Static non-linear cyclic pushover analysis was carried out to predict the seismic performance of the study frames. It was observed that the lateral strength of the infill frame is significantly higher compared to bare frame and open ground frame. All the frames started yielding from 0.75% drift level. The bare frame and open ground frame started showing load degradation after 2.75% drift level, while fully infilled frame started degrading after 3.5% drift level. Overall performance of fully infilled frame was found to be far better than that of the bare frame and open ground frame.

Djamal Yahmi, Taieb Branci, Abdelhamid Bouchair, Eric Fournely (2017) evaluates the seismic q-factor and its components stipulated in EC8. SMRFs are considered. It is shown that: (1) the structural lateral capacity of the frames studied increases as the capacity factor increases and the structural performance limit is influenced by the increase in the number of stories causing an increase in the risk of instability; (2) Neither the number of bays nor the lateral load patterns influenced the reserve strength factor except the stories number; (3) Regardless of the number of stories and bays all the frames analyzed have similar redundancy whose average value is higher than that recommended by EC8; (4) The highest values of the ductility factor, calculate with the triangular load, are obtained for low-rise frames under the global ultimate capacity; (5) The greatest values of the q-factor are obtained for low-rise frames and are higher than those of EC8. Therefore, a criterion related to the local ductility of column section ($N/N_{pl} < 0.40$) is proposed

III. CONCLUSIONS

The comprehensive review of studies indicates that the seismic vulnerability of soft story buildings is primarily governed by irregular stiffness distribution and localized force concentration at ground or lower stories. The accumulated evidence consistently reveals that these structural irregularities lead to higher story drifts, early formation of plastic hinges, and premature local failure under seismic excitation. Adrian and Oreta (2015) emphasize that such irregular configurations increase the risk of partial collapse unless appropriately addressed through meticulous design detailing. Enhancing stiffness regularity through structural systems such as eccentric bracings, as demonstrated by Khan and Rawat (2016), emerges as a cost-effective and reliable method to reduce drift concentrations and prevent catastrophic damage. The comparative assessment between OMRF and SMRF configurations (Cinitha et al., 2012) clearly reinforces the importance of ductility and controlled energy dissipation in seismic design, establishing SMRF as a preferred system for earthquake-resistant buildings. Furthermore, the inclusion of masonry infills, as explored by Basha and Kaushik (2016) and Oinam et al. (2017), contributes significantly to lateral capacity but requires careful consideration of material properties and interaction effects to avoid undesirable column shear failures. The findings of Yahmi et al. (2017) connect these behaviors with fundamental seismic performance parameters such as the q-factor and ductility ratio, reaffirming that structural stability is highly dependent on both global and local deformation capacities.

Collectively, the literature demonstrates that the seismic performance of RC frames with soft story configurations can be drastically improved through a combination of stiffness enhancement, ductility-based design, and performance-oriented evaluation frameworks. The review underscores the need for enhanced code provisions and experimental validation to address the limitations of current seismic design practices, particularly for infilled RC frames. Future research should focus on developing refined modeling techniques and validated design methodologies that can accurately predict the nonlinear performance of soft story structures under varying seismic intensities. Ultimately, reinforcing stiffness continuity and optimizing local ductility characteristics will be key to developing earthquake-resilient building systems capable of safeguarding life and minimizing structural loss.

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