Seismic Retrofitting of Structures Using Steel Bracing: An Overview

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doi: https://doi.org/10.21467/proceedings.112.32

ABSTRACT

One of the major causes of the collapse of buildings are earthquakes. Reinforced concrete structures are vulnerable to seismic activities and can destruct the structures. The RC structures which are prone to seismic activities should be protected and need to be retrofitted to resist the seismic loads. Retrofitting is one of the best methods which can be used to strengthen the structures safe against seismic loads. Retrofitting techniques will increase the strength, stiffness, ductility and stability of structures as well as reduce the operation costs and environmental impacts. Various techniques of retrofitting can be adapted to improve the stability of the structure. One of the most effective method for retrofitting of structures is the use of steel bracings. Steel bracing can be effectively used for enhancing the earthquake resistance of seismically inadequate reinforced concrete frames. This paper reviews the effect of different steel bracing patterns used as retrofitting technique in the seismic performance of the structures.

Keywords: Retrofitting, Reinforced concrete frames, Steel bracings, Strengthening

1 Introduction

Earthquakes are natural disasters which are one of the main causes of the collapse or damage of buildings and human-made structures. An earthquake causes severe damage in the forms of ground motions, ground failure and tsunamis. Ground motions are the principal causes of the earthquake induced damages to the construction industry. As a result of the occurrence of ground motion, the base of the buildings also vibrates according to it with varying intensity. The ground motion induces acceleration, velocities and displacement to the foundation of the structure. The structure responds to the transmitted accelerations from ground motions through its foundation. The superstructure also tends to move and vibrate from the state of rest with respect to the transmitted loads. But the state of inertia of the superstructures will concentrate the stresses induced from the ground motions in weak element and joints of the structure and thereby the failure or collapse of the structure occurs. One of the most earthquakes prone region in the world is the Indian subcontinent. About 60% of area of the India lies within the seismic zone of expected intensity of 7 and above. The structures are prone to seismic activities and should be protected from the unexpected seismic activities that may occur.

The main purpose of strengthening of structures is to keep the displacement demand of structures within its displacement capacity when an unexpected load such as seismic load act on it. This can be achieved by either reducing the displacement demand or increasing the displacement capacity of the structures. When new elements are added to the structures, it results in an increase in global stiffness and decreases the natural period of vibration of the structures. So, the addition of new members will increase the horizontal load capacity, thereby, there is a reduction in horizontal displacement which helps the structure to resist against earthquake load. The strengthening of structures will prevent the structure from collapse as well as delays structural

Proceedings DOI: 10.21467/proceedings.112; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-947843-3-3

damages also. Retrofitting is one of the best methods which can be used to strengthen the structures safe against seismic loads. Adding new structural elements such as steel bracing is an effective approach to strengthen the building subjected to seismic loads. Some benefits are also offered by the use of steel bracing systems for seismic retrofitting of RC frames, such as: (a) the ability to accommodate openings; (b) the minimum added weight of the structure; and (c) the installation of external steel systems with minimal disruption to the operation of the building and its occupants. Studies on different patterns of steel bracing that can be used for retrofitting of structures are reviewed and presented in this paper.

2 Studies on seismic retrofitting using steel bracings

Badoux and Jirsa (1990) investigated both analytical and experimental study of steel bracing systems for seismic retrofitting of reinforced concrete frames structures. Analytical study was carried out on multi-storey frames with different patterns of steel bracings such as X-patterns, diagonal pattern and K-pattern (Figure 1). And the experimental study was carried out on reinforced concrete frames with deep spandrel beams and short columns retrofitted with steel bracings. It was found that the steel bracings were very suitable for lateral strengthening and stiffening of multi-storey reinforced concrete structures. Also, combining bracing with beam alterations can greatly increase the inelastic behaviour of the braced frame.

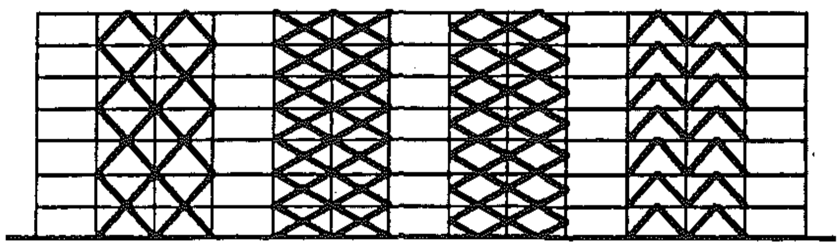

Figure 1: Different patterns of steel bracings (Badoux and Jirsa,1990)

Maheri and Sahebi (1997) performed an experimental investigation to find out the use of steel bracing in reinforced concrete frames by comparing the performance of unbraced and braced RC concrete frames. The models used represent a unit panel of arbitrary concrete frame subjected to horizontal earthquake force. Four models of frame without braces, with diagonal tension brace, with diagonal compression brace and with X-bracings were used. In-plane shear strength was evaluated for each frame by loading with compression testing machine and the load deflection curve for each model was plotted. Brace-frame connection was also investigated. It was found out that the bracings can be used as an alternative to shear wall with proper brace-frame connection.

Ghobarah and Elfath (2001) evaluated the performance of eccentric steel bracings system retrofitted in reinforced concrete frames. Different brace patterns that include V-bracing, K-bracing, X-bracing and Y-bracing were used in eccentrically braced steel frames. Static pushover analysis and dynamic time history analysis were conducted to find the seismic performance of the RC building retrofitted with eccentric steel bracing system. The effect of bracing distribution over varying height was also determined. It was found that the installation of steel eccentric bracings can improve the RC structures and can be efficiently used to rehabilitate

Proceedings DOI: 10.21467/proceedings.112

Series: AIJR Proceedings
ISBN: 978-81-947843-3-3
ISSN: 2582-3922

the reinforced concrete structures. It was suggested to select a brace distribution system which obtain a uniform distribution of story drift.

Maheri and Akbari (2003) evaluated the seismic behaviour (R) factor of X-bracing and knee bracing using three different frames of 4, 8 and 12 storeys by varying the base shear for the bracing. The base shear varies as 0%, 50% and 100% for steel bracing. Steel bracings were designed to withstand the load shares and the RC frames were designed to withstand the remaining base shear specified by the code. Inelastic pushover analysis was done using DRAIN-2DX program. The effect of brace load share, number of storeys and the types of bracing on the R factor were evaluated. Figure 2 shows the effect of R value of the RC frames with different type of bracings. The R factor depends on the height of the frame, that is, shorter frame exhibits more R value and therefore high ductility. Higher ductility value was provided by knee bracings among others.

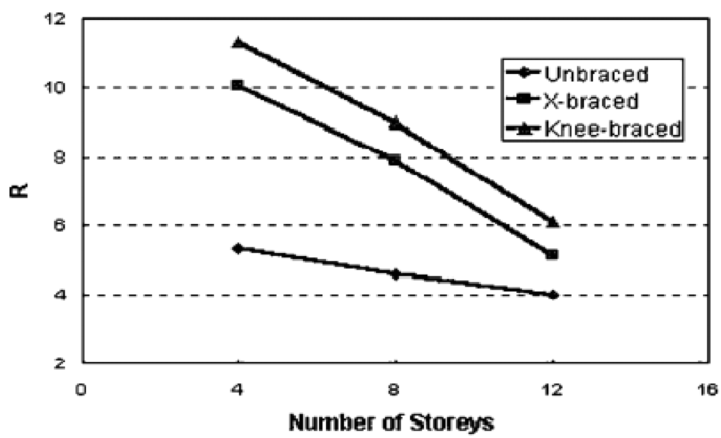

Figure 2: Effect of bracings on the seismic behaviour factor (Maheri and Akbari, 2003)

Maheri et al. (2003) conducted pushover analysis on RC frames retrofitted with X-bracing and knee bracing to investigate the effectiveness of bracing system as a retrofitting measure in RC frames. RC frame of 4-storey with 3 bays scaled to 1:3 without and with both bracings were used as the model to conduct the pushover analysis. Load capacity, stiffness, toughness, ductility, overstrength and performance factor were evaluated. Both X and knee bracing systems can resist the damage-level earthquake but knee bracing was most suitable for the collapse-level earthquake.

Maheri and Hadjipour (2003) conducted an experimental investigation on different types of connections that can be used for the brace-frame in RC frames. The first connection type was a normal corner connection type for connecting X-bracing to the junction of the beam and column. In this connection, the brace was welded to the gusset, which was welded to the connecting plates, and using hooked anchor bolts, these connecting plates were bolted to the frame. The second type of connection is identical to the first one except that the straight bolts were used to connect the connecting plates. In the third form of connection, the corner of the frame was constructed with concrete so that only one connecting plate was required to transfer the brace load directly through the joint. Compression test was conducted on the constructed full-scale connection types, and the force-displacement response of each connection type was evaluated. It was found out that the first and second connection types provide more robust connection due to their load transferring manner, whereas, the third connection type can be used to improve the overall ductility of the connection.

Perera et al. (2004) conducted analytical and experimental investigation on masonry infilled reinforced concrete frames retrofitted with K-bracings connected using vertical shear link. Three different models of damaged models for frame, damaged model for masonry infills panels and a model with vertical shear link element were modelled for the numerical evaluation. For the experimental program, a four storey RC frame retrofitted with eccentric bracing using vertical shear link was designed. The experimental and analytical study showed that the retrofitting using steel bracings improves the ductility of the frame. It was also found out that the vertical shear link imposes an excellent energy dissipation capacity.

Maheria and Ghaffarzadeh (2008) performed both experimental and analytical investigation to evaluate the connection overstrength in RC steel braced frames. Experimental study was conducted by performing cyclic load test in three model frames of one moment frame and others with bracing. Frames of 4, 8 and 12 storeys installed without and with X-bracing were modelled to conduct pushover analysis in OpenSees software. From the experimental and numerical analysis, it was found that the presence of overstrength in braced frame was due to the stiffening effects of connections. The level of interaction between the strength capacities of the RC frame and the bracing system were also studied. The most important parameters affecting capacity interactions were found to be number of bays, number of storeys of the frame and stiffness ratio.

Durucan and Dicleli (2010) performed an analytical investigation to upgrade the seismically vulnerable reinforced concrete buildings using a proposed seismic retrofitting system which consists of a rectangular steel frame retrofitted using chevron bracings and a shear link between them. Different configuration of the proposed retrofitting system was studied using ANSYS and the suitable configuration was selected and further investigation was carried out. A selected RC building was installed with the proposed retrofitting system and the nonlinear pushover and nonlinear dynamic analysis was carried out. The analyses results shows that the proposed retrofitting system ensures satisfactory performance and less damage.

Akbari and Maheri (2013) evaluated the ductility, the overstrength factors and the response modification factor for steel chevron-braced RC frames. Inelastic pushover analyses were performed in brace-frame systems of different heights and configurations. The parameters like the height of the frame and share of bracing system from the applied lateral load which influence the value of behaviour factor were also investigated. It was found that the steel-braced RC dual systems possess much larger ductility when compared to their equivalent un-braced moment-resisting RC frames when it is designed for a specific base shear. It was found that R factor decreases with the increase in number of storeys. This was due to influence of the share of steel bracing from the base shear. The effect of number of storeys on the R value of chevron-braced frames was shown in figure 3.

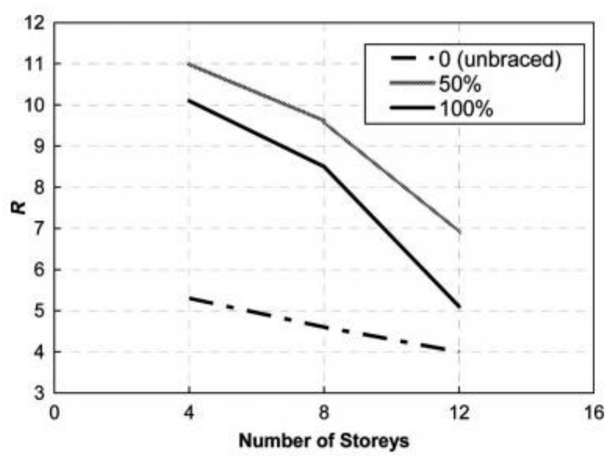

Figure 3: Effect of number of stories on the R value of chevron-braced frames

(Akbari and Maheri, 2013)

Safarizki et al. (2013) conducted a static pushover analysis to study the effect of steel braces in reducing target displacements. The model of an existing structure was designed and linear static analysis was carried out using ETABS software. The analysis was continued until it reaches the yielding point and the results obtained was compared with the target displacement calculated with the Displacement Coefficient Method of FEMA 356 and Displacement Coefficient Method of FEMA 440. The deflection from the pushover analysis exceeds the target displacement calculated and so, the building was classified between the life safety to collapse prevention category. The same method was followed for the retrofitted structure, and it was found out that the steel braces reduce the target displacements.

Javadi and Yamakava (2013) conducted an experimental study on the frame retrofitted with inverted V-bracings connected using hybrid connection and suggested that hybrid connection technique can be effectively used to provide connection between existing reinforced concrete frame and steel braced frame. In hybrid connection, two base plates were used to connect the bracings to the RC frame and anchor bolts were used to connect the base plates with the stub. The high direct shear between the RC frame and the steel bracing was effectively conveyed with the help of hybrid connection. This type of connection also helped to increase the axial compression capacity and shear strength of the RC columns.

Faella et al. (2014) studied the effect of different steel bracing configurations on the seismic response of an existing structure. The existing structure and the structure retrofitted by three different diagonal patterns were modelled and analysed to find out the seismic behaviour of the structure. It was concluded that the three diagonal patterns have a positive influence in the seismic behaviour of the structure and it controls the actual lateral capacity of the retrofitted structures. It was also suggested that the bracing system should be carefully selected to avoid retrofitting costs of unfavourable bracing system.

Ramin (2014) investigated the steel off-diagonal bracing system (ODBS) as a retrofitting technique in reinforced concrete. RC frame models of 2, 6 and 15 - storeys with the different bracing patterns was modelled using SAP2000 and micro-modelling was done in ANSYS. First bracing pattern consists of ODBS at the lower storeys and the X-bracing in the upper storeys. The other pattern contains X-bracing on all the storeys. OBDS increases the base shear and storey drift, thereby, increases the flexibility whereas, the addition of X-bracing decreases the ductility of the frame. The bracing system was not suitable for high storey buildings. However, an extra strength of 10-45 % was gained by adding ODBS.

Navya and Agarwal (2016) conducted a study on seismic retrofitting of structures by steel bracings by IS 456:2000 and IS 1893 (Part 1):2002 codes. In comparison to the unconfined condition, the pushover analysis of the building designed according to IS 1893 (Part 1): 2002 on the basis of confined plastic hinge regions performs very satisfactorily. Fragility curves demonstrates that conventionally designed building was more prone than the seismically designed buildings. Building designed in accordance with 1893 (Part 1): 2002 undergo moderate damage under the same level of the seismic hazard. After retrofitting with steel bracing, a major reduction in the seismic vulnerability of the building was confirmed.

Maheri and Yazdani (2016) performed the numerical analysis using the same three types of connection used by Maheri and Hadjipour (2003) for experimental work using ANSYS software. SOLID45 elements were used to model the frame and SOLID65 elements were used to model the steel bracings and connections. Parameters such as lateral capacity, stiffness, energy dissipation capacity and ductility were evaluated to find the seismic behaviour of the braced frames installed with different connection techniques. Similar results as that of the experimental work was obtained. It was found that the all three type of connections transmit the load between frame and brace effectively. However, the third connection type shows better performance when compared to the other two connection type.

Qian et al. (2017) conducted an experimental investigation to study the effect of bracing on the behaviour of RC multi-story frames to resist progressive collapse. Three test models having 3 multi-storey heights without bracings, with concentric and eccentric X-bracings which were installed externally were designed for the experimental study. The results showed that shear failure of exterior joint occurred in the bare frame, whereas high initial stiffness was experienced in the braced frames which helped to mitigate the progressive collapse. It was concluded that the steel bracing installed externally to the frames have the capability to improve the frame from progressive collapse. Also, from the experimental study, it was suggested that the eccentric bracings were better than that of concentric bracing system.

Ramin and Maheri (2018) compared seismic retrofitting of structures with off diagonal steel bracings with other bracings such as X-bracings and inverted V-bracing. Three different RC frames of 5, 10 and 15 storeys were retrofitted with the different bracing systems and were subjected to dynamic time history records and cyclic loading. Also, the natural period of vibration and modal participation of main modes of vibration were evaluated by modal analyses. Results from hysteresis responses showed that the ODBS have highest amount of dissipated energy and the compression capacities compared to the other bracing systems. Results from the time history records and the cyclic loading showed that the ODBS have greater number of modes participating in the response of the frame.

Rahimi and Maheri (2018) investigated three different RC frames retrofitted with X-bracing to determine its effect on the seismic behaviour of columns. The three RC frames of 4-storey, 8-storey and 12-storey having 3 bays were used, in which the dimensions of both bracing and the frames decreases to the upper stories. OpenSees software was used to execute the dynamic nonlinear time history analysis of the RC frame-steel brace unit and the earthquake records selected for the analysis were from provisions of ASCE/SEI 7-10. Shear, and axial force on the performance of the middle and side columns were evaluated. Also, the column performance level and the fatigue life were investigated. Four-storey frames, that is, low rise frame shows better performance in all terms compared to the other frames when retrofitted with X-bracings.

Ren et al. (2019) evaluated the seismic performance of irregular RC–steel hybrid frame with respect to parameters such as residual displacement, story drift ratio, roof displacement, and hysteretic energy ratio. The hybrid frame is a vertical combination of a newly added steel frame and a pre-existing RC frame and was subjected to seismic loads of different intensity. A hybrid frame was installed with new frames, steel bracings, concrete shear wall and their combinations to evaluate the seismic performance. It was found that in retrofitting pre-existing RC frames, the concrete shear walls minimize the roof displacement and story drift ratios, whereas more uniform distribution of story drift ratios was implemented by steel braces.

Qian et al. (2019) conducted experimental investigation using different bracing configurations including concentric and eccentric X-bracing, V and reversed V-bracing. Parameters such as load resisting capacity, stiffness and dynamic load capacities were evaluated. The eccentric X-bracing was more efficient in terms of load capacity whereas the V and reversed V-bracing were more efficient in terms of stiffness. All the bracing has the capability to improve the dynamic load capacity, but concentric X-bracing was most efficient due to its brittle failure nature.

Rahimi and Maheri (2020) investigated various parameters like maximum lateral displacement, base shear, inter-storey drift, ductility in beams and the overall performance of the frame and its elements when retrofitted with

X-bracing. It was concluded that the X-bracing have the capability to improve the seismic behaviour of frames under earthquake loads but were less effective as the storey height increases. Figure 4 shows the average displacements versus displacement reduction percentage after retrofitting. Figure 5 shows the increase in average base shear after retrofitting.

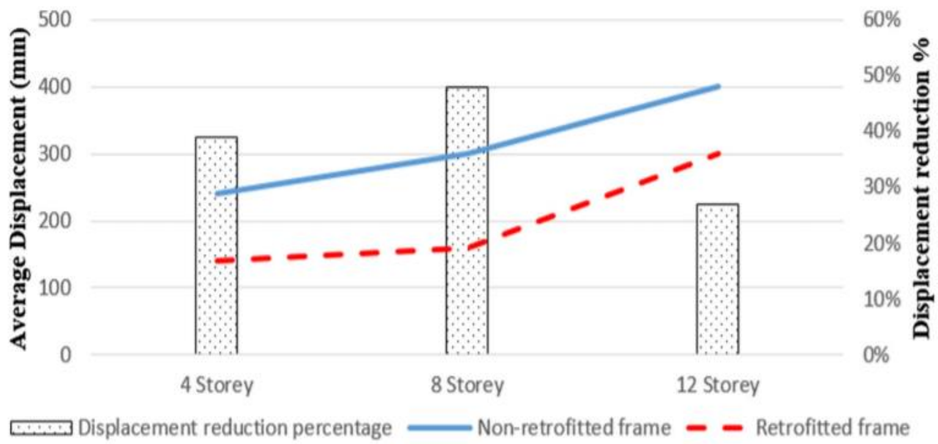

Figure 4: Average displacements versus displacement reduction percentage (Rahimi and Maheri, 2020)

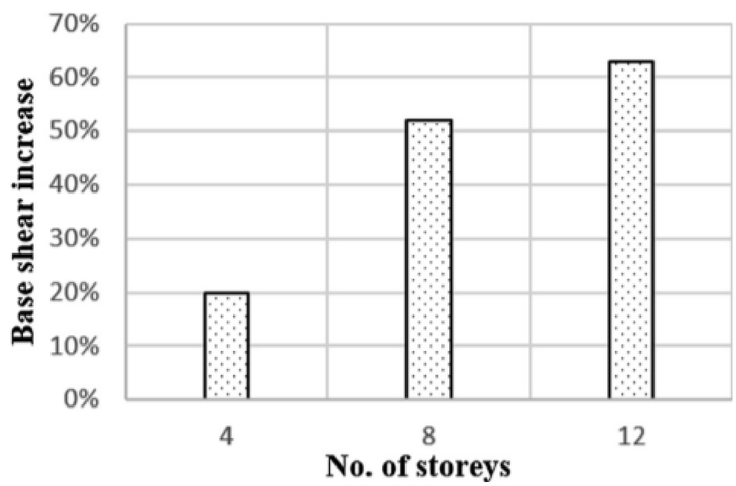

Figure 5: Increase in average base shear after retrofitting (Rahimi and Maheri, 2020)

Formisano et al. (2020) suggested that the external arrangement of the bracing systems helped to minimize the impacts caused to the existing building during the retrofitting works without any interruption. The seismic vulnerability of reinforced concrete (RC) buildings designed to gravity loads was discussed. Three different models of the building to highlight the role of the infill walls arrangement were selected and named as bared frame, full infilled frame and pilot's frame. The three models had been retrofitted with the external bracing systems and the seismic performance was evaluated. The external arrangement of the bracing systems had been chosen in order to both minimize the impact on the existing building and avoid the local interaction between the RC structural elements and the steel bracings. The results showed that the strong role of the infills in the structural behaviour of the existing building and the efficiency of the external steel bracing systems as retrofitting technique of existing RC buildings.

3 Conclusion

This paper reviewed the effect of steel bracings and its different bracing configurations on the seismic response of RC structure. From the review of literature, the following conclusions can be derived:

- Steel bracings is an effective retrofitting technique which improves the seismic performance of the structure.
- Steel bracing can be used for lateral strengthening and can achieve the stability ranging from drift control to collapse prevention.
- The geometry and shape of the steel bracings have a great influence in the seismic behaviour of the structure.
- Concentrically braced frames are more efficient than eccentric bracings and can be easily retrofitted.
- X-bracings are found to be more effective than other bracings in overall performance of the frame.

How to Cite this Article:

Silpa, S., & Joy, C. M. (2021). Seismic Retrofitting of Structures Using Steel Bracing: An Overview. *AIJR Proceedings*, 253-261.

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