Seismic performance of exoskeleton structures in irregular buildings

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Abstract. Exoskeleton Structure is a diagrid like structure used for retrofitting existing structures. This paper evaluates the seismic performance of exoskeleton structures on buildings with plan irregularity. Linear dynamic analysis using Response Spectrum method is carried out. L shaped building frames with A/L ratios of 0.15, 0.30 and 0.50 are considered in the present study. The results show that exoskeleton structure is capable of reducing response parameters such as shear force, floor displacement and forces in columns.

1. Introduction
In the current scenario of stringent seismic requirements imbibed in various codes, retrofitting of existing buildings to required performance is quite challenging to practicing structural engineers. Conventional retrofitting techniques including addition of shear walls, addition of infill walls and addition of braces are quite cumbersome both from construction and functional viewpoint. These conventional techniques affect the functional aspect of the structures and in most cases involve strengthening of existing foundation. These conventional techniques can make the structure temporarily out of use during strengthening which is not feasible, at least for some structures. All these issues could be overcome by external retrofitting strategies. Majority of conventional retrofitting make use of strengthening concept. While techniques like base isolation make use of reducing seismic demand concept. In external retrofitting strategies also, seismic demand reduction is mainly adopted.

Exoskeleton structures are external self-supporting diagrid like structural system suitably connected to primary structure in order to improve the seismic performance of primary structure. Exoskeleton structure acts as sacrificial element and absorbs forces and rigid links are used to connect exoskeleton structures with the building to be protected.

The structural control using exoskeleton structures largely depends on the structural properties of rigid links and their connection with the main building. The connection between the existing and external structure could be rigid or flexible. A higher stiffness of the link is required to alter the time period of higher modes[1]. Acceleration of floors were found to be increased with inclusion of exoskeleton structures [2]. There must be a trade-off between displacement control and acceleration control. In addition to displacement/acceleration control, exoskeleton structures were found to be effective in reducing base shear too. A considerable part of the base shear induced due to seismic actions was found to be shared by the exoskeleton structure, reducing the base shear of the building frame to be controlled [3]. As of now only studies with rigid connections are available in case of exoskeleton structures.
Exoskeleton structures can be modelled as a coupled primary-secondary oscillator system as shown in Figure 1. M1, K1, C1 are mass, stiffness, damping coefficient of primary oscillator and M2, K2, C2 are mass, stiffness, damping coefficient of secondary oscillator. K is the stiffness of the connecting link.

![Figure 1. Structural model (Source: [3]).](image)

No studies have so far been reported on exoskeleton structures connected to irregular structures. The present paper discusses the efficiency of exoskeleton structures on plan irregular structures.

2. Details of building configuration

In the present study, typical RCC frames of regular and irregular configurations are considered. The regular frame considered is having a square plan. Irregular frames considered are L-shaped frames (in plan). i.e., irregularity is introduced by a re-entrant corner as illustrated in IS 1893 (Part 1):2016 (Figure 2). The overall plan dimensions (total width in either directions) of the irregular frames are kept same as those of the regular frame.

![Figure 2. Irregularity due to re-entrant corner (Source: [4]).](image)

The regular frame considered in the study has a square plan (L/B = 1) having dimensions of 24 m × 24 m, with 4 bays of 6 m span along both directions. The height of the building considered is 12 m, with 4 stories of 3 m height. Exoskeleton structure is provided outside the periphery of the building at a distance of 100 cm. The exoskeleton structure is connected to the building at various floor levels by links.

The plan and elevation of the regular building, considered in the study, with exoskeleton structure is shown in Figure 3.
Figure 3. Configuration of regular building frame (L/B=1) connected with Exoskeleton Structure (a) Plan (b) Elevation.

As one may observe (Figure 2), the A/L ratio defines the degree of irregularity. As per IS 1893, the frame is considered irregular when A/L exceeds 0.15. Frames with different values of A/L ratios of 0.15, 0.30 and 0.50 are considered. The plans of these frames are shown in Figure 4.

Figure 4. Plan of irregular frames with different A/L ratios (a) A/L=0.15 (b) A/L=0.3 (c) A/L=0.5.

The number of stories (4) and storey height (3 m) of all frames are kept the same. The sizes of beams, columns and slabs of the frame are: Beam size - 400 mm × 300 mm, Column size- 400 mm × 400 mm, Slab thickness- 120 mm. Grade of concrete and rebar are M25 and Fe 415 respectively.

Exoskeleton structures are made of Fe250 grade steel. Columns are made of I sections (ISLB 200), diagonal beams in exoskeleton structures is hollow circular beams (114.3 mm × 5mm) at inclination of 45 degrees. Location of exoskeleton structures is 100 cm from outside perimeter of building. The building frame (bare frame) is connected to the exoskeleton structures using links. The link is a rod of 10 cm diameter and 100 cm length. The links are modelled as axially rigid links by releasing moments. The Young’s Modulus (E) of the link is assumed to be $2 \times 10^{13}$N/mm$^2$. A high value of E is chosen to increase the axial stiffness of the link to make it as rigid as possible.

3. Seismic analysis
Linear dynamic analysis using Response Spectrum method was carried out in ETABS for frames of all four configurations – regular frame and L-shaped frames with A/L=0.15, 0.30 and 0.50. The frame without exoskeleton is referred as bare frame in the following sections.
Total eight models – four bare frames and four frames with exoskeleton structures – were analysed. The response spectrum given in IS code for Zone III was considered in the analysis. The importance factor (I) adopted is 1.5 and response reduction factor (R) of 3 is adopted. Response Spectrum analysis involves calculation of responses in each mode of vibration and combining them using suitable modal combination rules. In the present analysis, Square Root of Sum of Squares (SRSS) method as suggested in IS 1893 (Part 1):2016 is adopted for modal combination.

4. Results and discussions

Responses such as base shear and floor displacements of both the bare frame and exoskeleton with rigid link are considered for comparing the seismic performance of frames. Irregularity induces torsion and hence torsional responses are also considered for investigating the control effectiveness of exoskeleton structures. The maximum values of bending moment, twisting moment and shear force in the corner columns are considered for the study.

To indicate the control effectiveness, a control parameter (Cr) is defined as given below:

\[ C_r = \frac{r_{\text{uncontrolled}} - r_{\text{controlled}}}{r_{\text{uncontrolled}}} \]  

(1)

Here \( r \) is the response parameters considered in the present study such as base shear, storey displacement and forces in columns. Also the uncontrolled response refers to the response of the frame without any control measures (bare frame) and controlled response refers to the response of frame strengthened with exoskeleton structure.

4.1. Floor displacements

The maximum displacements of various floors for various configurations of frames are shown in figure 5.

**Figure 5.** Variation of floor displacements different types of frames.
Figure 6. Displacement control of exoskeleton structures for frames of different configurations.

From the above graphs it is evident that displacement of the storey is effective controlled by using exoskeleton structures. The control effectiveness with respect to top floor displacement (C\textsubscript{TFD}) - i.e. percentage reduction in top floor displacement of exoskeleton frame compared to the bare frame – for frames with L/B=1, A/L=0.15, A/L=0.30 and A/L=0.50 are respectively 55.31%, 42.96%, 59.36% and 56.20%.

4.2. Base shear

The maximum base shear induced in frames of different configurations are provided in Table 1.

Table 1. Maximum base shear induced in frames.

| Frame Configuration | Base shear (bare frame) (kN) | Base shear (exoskeleton) (kN) | Control Effectiveness (C\textsubscript{BSH}) |
|---------------------|-----------------------------|-----------------------------|----------------------------------------|
| L/B=1               | 590.39                      | 196.47                      | 66.72 %                               |
| A/L=0.15            | 651.34                      | 355.79                      | 45.37%                                |
| A/L=0.30            | 645.14                      | 252.14                      | 60.87%                                |
| A/L=0.50            | 518.08                      | 180.73                      | 65.11%                                |

From the above table it is observable that the exoskeleton structure is effective in controlling the base shear for frames of all configurations considered in the present study.

4.3. Forces in corner columns

Maximum values of BM, TM and SF in the columns located at all corners are taken and the maximum of each are noted. The maximum values of each of these responses in corner columns are tabulated in Table 2. The control effectiveness is also shown.
Table 2. Maximum response of corner columns.

| Details          | Maximum response |          |          |
|------------------|------------------|----------|----------|
|                  | BM (kNm)         | SF (kN)  | TM (kNm) |
| Regular          |                  |          |          |
| B/L = 1          | Bare frame       | 54.00    | 20.79    | 0        |
|                  | Exoskeleton      | 25.54    | 9.85     | 2.45     |
|                  | Control effectiveness | 52.7 %  | 52.6 %   | --       |
| Irregular        | Bare frame       | 70.63    | 52.68    | 4.33     |
| A/L = 0.15       | Exoskeleton      | 27.69    | 19.62    | 2.85     |
|                  | Control effectiveness | 60.79%  | 62.75%   | 34.11%   |
| Irregular        | Bare frame       | 79.10    | 30.45    | 3.08     |
| A/L = 0.3        | Exoskeleton      | 28.32    | 10.89    | 0.61     |
|                  | Control effectiveness | 64.19%  | 64.23%   | 80.19%   |
| Irregular        | Bare frame       | 74.74    | 30.50    | 1.65     |
| A/L = 0.50       | Exoskeleton      | 21.61    | 8.82     | 2.18     |
|                  | Control effectiveness | 71.08%  | 71.08%   | -32.1 %  |

The above tables show that there is considerable reduction in the maximum values of bending moment and shear forces induced in the corner columns in frames of all configurations. However, exoskeleton structure is not found to be effective for controlling torsional moments for frames with L/B=1 and A/L=0.50. For the other two frames, the control effectiveness with respect to torsional moment, is found to be reducing with increase in A/L ratio.

5. Conclusion

Exoskeleton structure is a suitable retrofitting strategy especially in situations where space constraints and functional constraints are present. Performance of exoskeleton structures in the seismic response control of regular and plan irregular frames are considered in the present study. Of the several ways of connecting the exoskeleton with the bare frame, rigid links with hinged connection is adopted in the present study. The study suggests that the exoskeleton structure is capable of reducing floor displacements and base shear in plan irregular as well as regular structures. Control effectiveness is found to be excellent. However, exoskeleton structure is not found to be effective for controlling the torsional moments induced in the corner columns of plan irregular frames. Only a linear dynamic analysis is presently chosen. More insights into the seismic behavior of exoskeleton structures may be obtained from nonlinear dynamic analysis.

6. References

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