Abstract

During an earthquake, a brittle punching failure can arise in flat plate-column connections due to poor transfer capacity of shearing forces and unbalanced moments. To increase the shear capacity of the slab, various types of shear reinforcement can be used in the slab around the connection. The aim of the project is to study the response of slab column connections containing with various slab shear reinforcement when subjected to combined gravity and cyclic lateral loading. At first a calibration model was developed to simulate the tested flat plate-column joint using finite element analysis program MASA. This model was used to predict the load displacement behaviour. The results showed that the model predicts the load level excellently but significantly over estimates the stiffness of the joint compared to that observed by James Lee & Ian Robertson. Since the present study is to compare the relative behaviour of slab-column joints provided with various slab shear reinforcement, the error in the estimation of joint stiffness will not alter the comparative conclusions drawn. Thus, the developed model was validated for application to various types of column slab connection behaviour.
1. Introduction

Flat plate is one of the most common floor systems for large span commercial buildings. The advantages of a flat-Plate floor system are numerous. It provides architectural flexibility, more clear space, less building height, easier form work, and, consequently, shorter construction time. Low floor to floor heights reduce the total building height, thus reducing lateral loads, cost of building cladding, cost of vertical mechanical and electrical lines, and air conditioning/heating costs. For vertical loads, the structural performance and design of flat plates are well established. Under lateral loads, many aspects of the behavior of flat plates are uncertain. A serious problem that can arise in flat plates is brittle Punching Shear failure due to poor transfer capacity of shearing forces and unbalanced moments between slabs and columns. In seismic zones, a structure can be subjected to strong ground motions, and, for economical design, a structure is considered to undergo deformations in the inelastic range, therefore, in addition to strength requirement, slab-column connections must undergo these inelastic deformations without premature punching or shear failure. In other words slab column connections must have adequate ductility.

2. Methodology

- Literature review on studies of slab column joints and Finite element analysis of reinforced concrete structures.
- Developing of calibration model to simulate the tested flat plate-column connections.
- Developing of finite element model to study the behavior of flat plate-column connections without slab shear reinforcement.
- Come up with recommendations to improve the ductility of flat plate column joint under seismic loads.

3. Various Types Of Shear Reinforcements

<table>
<thead>
<tr>
<th>Sl.no.</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NS</td>
<td>No slab shear reinforcement (Fig.5)</td>
</tr>
<tr>
<td>2</td>
<td>SLS_I</td>
<td>Single leg stirrups spread over a width equal to the column width in both the directions. (Fig 6)</td>
</tr>
<tr>
<td>3</td>
<td>SLS_II</td>
<td>Single leg stirrups spread over a width equal to six times the column width in both the directions. (Fig 7)</td>
</tr>
<tr>
<td>4</td>
<td>LCY_I</td>
<td>Inclined leg lacing type shear reinforcement as shown in Fig 8.</td>
</tr>
<tr>
<td>5</td>
<td>LCY_II</td>
<td>5 Inclined leg lacing type shear reinforcement spread over a width equal to six times the column width in both the directions as shown in Fig 9.</td>
</tr>
<tr>
<td>6</td>
<td>VLCY</td>
<td>Vertical leg lacing type shear reinforcement spread over a width equal to six times the column width in both the directions as shown in Fig 10.</td>
</tr>
</tbody>
</table>

3.1 Analysis model

An interior flat plate column connection is considered for the analysis. The geometry and the reinforcement details are as shown in the figures 1 and 2 respectively. M30 grade of concrete, Fe 415 grade of steel for main reinforcement and Fe 250 grade steel for shear reinforcement are adopted in the analysis. The column is modeled with linear elastic material so as not to yield prior to slab flexural yielding. Finite element modeling package, FEMAP is used to model the Flat plate column joint. Following are the steps involved in the modeling of joint.
Solid elements are used to model concrete and bar elements are used to model reinforcement.

- Slab is allowed to translate in loading direction alone and constrained in other (Y & Z) directions. Gravity load is applied on the slab in the form of point loads.
- Bottom of the column is hinge supported and the predetermined cyclic lateral displacement routine is applied at the top of the column.
- The Bond to the reinforcement is modeled by inputting Bond-Slip curve in the analysis.
- The finite element model developed in FEMAP is transferred to MASA for the analysis.

The finite element mesh for the analysis model is as shown figure 3. The location of constraints and points of loading are shown in the figure 4. The figures from 5 to 10 show the reinforcement layout for models with various types of slab shear reinforcement.
Figure 3: Finite element mesh for the Analysis Model

Figure 4: Loading and Constraints

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Figure 5: Reinforcement Layout for model without slab shear reinforcement (NS)

Figure 6: Reinforcement Layout for model with single leg stirrups (SLS_I)

Figure 7: Reinforcement Layout for model with single leg stirrups (SLS_II)

Figure 8: Reinforcement Layout for model with inclined-leg Lacing (LCY_I)
The cyclic lateral displacement routine is applied at the top of the column for all models. The lateral displacement routine used in the analysis is shown figure 11.

4. Results Of Analysis Model

The hysteretic load deformation curves for Flat plate-column models with various types of Slab shear reinforcement is plotted as shown below.

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Figure 12: Load deflection hysteretic curve for model without slab shear reinforcement (NS)

Figure 13: Load deflection hysteretic curve for model with single leg stirrups (SLS_I)

Figure 14: Load deflection hysteretic curve for model with single leg stirrups (SLS_II)
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Figure 15: Load deflection hysteretic curve for model with inclined-leg Lacing (LCY_I)

Figure 16: Load deflection hysteretic curve for model with inclined-leg Lacing (LCY_II)

Figure 17: Load deflection hysteretic curve for model with vertical-leg Lacing (VLCY)
The figure 18 shows the deformed shape for the model without slab shear reinforcement (NS).

Side view

Figure 18: Deformed Shape for the model without slab shear reinforcement (NS)

The figures 19 and 20 show the crack pattern and stresses in reinforcing bars at the joint respectively observed in the model without slab shear reinforcement.

Figure 19: Crack pattern for the model without slab shear reinforcement (NS)
Analysis results from MASA are shown in table 4.2. This table shows lateral load sustained by the various models and corresponding displacement both at peak and at the ultimate.

Table 2: Analysis results for FE models with various types of slab shear reinforcement

<table>
<thead>
<tr>
<th>Type of Shear Reinforcement</th>
<th>Cycle</th>
<th>Peak Lateral Load (kN)</th>
<th>Displacement at Peak Load (mm)</th>
<th>Lateral Load at Ultimate (kN)</th>
<th>Displacement at Ultimate Load (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>Positive</td>
<td>18.07</td>
<td>12.00</td>
<td>12.22</td>
<td>24.00</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>-15.84</td>
<td>-8.00</td>
<td>-6.48</td>
<td>-24.00</td>
</tr>
<tr>
<td>SLS_I</td>
<td>Positive</td>
<td>21.81</td>
<td>16.00</td>
<td>17.74</td>
<td>28.00</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>-17.34</td>
<td>-12.00</td>
<td>-9.68</td>
<td>-24.00</td>
</tr>
<tr>
<td>SLS_II</td>
<td>Positive</td>
<td>21.50</td>
<td>16.00</td>
<td>21.14</td>
<td>20.00</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>-17.23</td>
<td>-12.00</td>
<td>-12.70</td>
<td>-32.00</td>
</tr>
<tr>
<td>LCY_I</td>
<td>Positive</td>
<td>19.48</td>
<td>12.00</td>
<td>15.54</td>
<td>20.00</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>-16.72</td>
<td>-12.00</td>
<td>-9.82</td>
<td>-32.00</td>
</tr>
<tr>
<td>LCY_II</td>
<td>Positive</td>
<td>19.84</td>
<td>12.00</td>
<td>11.89</td>
<td>28.00</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>-16.61</td>
<td>-8.00</td>
<td>-14.92</td>
<td>-24.00</td>
</tr>
<tr>
<td>VLCY</td>
<td>Positive</td>
<td>20.59</td>
<td>12.00</td>
<td>12.66</td>
<td>28.00</td>
</tr>
<tr>
<td></td>
<td>Negative</td>
<td>-16.61</td>
<td>-8.00</td>
<td>-12.72</td>
<td>-28.00</td>
</tr>
</tbody>
</table>
5. Conclusions

Three calibration models are developed to validate the finite element modeling and analysis software’s FEMAP and MASA respectively. Six interior flat plate-columns connections with various types of slab shear reinforcement are modeled and analysed under combined gravity and cyclic lateral loading. Based on comparison of the results of these models, the following conclusions are drawn:

- Punching shear failure can arise in case of flat plate-column joint without slab shear reinforcement. It is brittle failure which reduces lateral load carrying capacity of connection suddenly.
- All types of slab shear reinforcement, namely, single-leg stirrups (SLS_I & SLS_II) and lacing type shear reinforcement (LCY_I, LCY_II & VLCY), are effective in resisting punching shear failure of the flat plate-column joint under combined gravity and cyclic lateral loading.
- Use of Slab shear reinforcement improves the overall behaviour of the connection in terms of ductility, energy dissipation capacity, resisting punching failure and drift capacity.
- The ductility of the joint under monotonic loads is significantly higher than that under cyclic loading. Under Monotonic loading use of slab shear reinforcement does not affect much the behaviour of connection.
- Grade of steel of slab shear reinforcement does not affect much the behaviour of the connection.
- Both lacing type and single leg stirrups are effective in improving the overall behaviour of the connection but lacing type shear reinforcement is recommended since it is easy to install and does not require welding which suits Indian site conditions.

References