CHAPTER 7

COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

7.1 OVERVIEW

The accuracy of the proposed analytical model described in Chapter 6 was verified, by comparing the analytical results with the experimental results for the specimens tested in this study. The comparison of the analytical results with experimental results is presented in this chapter.

7.2 COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

The comparison of the experimental and analytical results for the test specimen is made in terms of the moment versus rotation, column shear versus drift ratio, beam elongation versus drift ratio and energy dissipation capacity.

The ratios of $\frac{M_{\text{Test}}}{M_{\text{Ana.}}}$ and $\frac{V_{c\text{ Test}}}{V_{c\text{ Ana.}}}$ are presented in Table 7.1, where $M_{\text{Test}}$ and $M_{\text{Ana.}}$ are the maximum flexural beam moments from the experimental and analytical results respectively, while $V_{c\text{ Test}}$ and $V_{c\text{ Ana.}}$ are the maximum storey shear from the experimental and analytical results respectively. It is clearly observed that the ratio $\frac{M_{\text{Test}}}{M_{\text{Ana.}}}$ in both positive
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Description</th>
<th>Max. Test flexural moment (kN.m)</th>
<th>Max. Analytical flexural moment (kN.m)</th>
<th>$M_{\text{Test}} / M_{\text{Ana.}}$</th>
<th>Max. Test shear (kN)</th>
<th>Max. Analytical shear (kN)</th>
<th>$V_{\text{c Test}} / V_{\text{c Ana.}}$</th>
<th>$M_{\text{Test}} - M_{\text{Test}}$</th>
<th>$M_{\text{Ana}} - M_{\text{Ana}}$</th>
<th>$V_{\text{c Test}} - V_{\text{c Test}}$</th>
<th>$V_{\text{c Ana}} - V_{\text{c Ana}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBCJ-1</td>
<td></td>
<td>37.33</td>
<td>37.29</td>
<td>1.00</td>
<td>1.04</td>
<td>70.55</td>
<td>67.19</td>
<td>-65.19</td>
<td>-58.87</td>
<td>-66.11</td>
<td>-63.54</td>
</tr>
<tr>
<td>SBCJ-2</td>
<td></td>
<td>40.97</td>
<td>39.37</td>
<td>1.04</td>
<td>1.04</td>
<td>89.83</td>
<td>85.72</td>
<td>-88.31</td>
<td>-82.30</td>
<td>-84.22</td>
<td>-82.52</td>
</tr>
<tr>
<td>SBCJ-3</td>
<td></td>
<td>42.89</td>
<td>42.32</td>
<td>1.05</td>
<td>1.05</td>
<td>95.84</td>
<td>93.57</td>
<td>-90.48</td>
<td>-89.87</td>
<td>-90.48</td>
<td>-91.66</td>
</tr>
<tr>
<td>SBCJ-4</td>
<td></td>
<td>44.96</td>
<td>42.33</td>
<td>1.06</td>
<td>1.06</td>
<td>98.57</td>
<td>93.76</td>
<td>-92.69</td>
<td>-92.42</td>
<td>-92.69</td>
<td>-91.63</td>
</tr>
</tbody>
</table>

Table 7.1: Comparison of the experimental and analytical results
and negative loading directions are closer to the value of 1.0 for the specimens SBCJ-2, 3 and 4 (Figures 7.2, 7.3 and 7.4) whereas the ratio $M_{\text{Test}} / M_{\text{Ana.}}$ is slightly over estimated especially in the positive loading direction for this specimen in both positive and negative directions. However, the initial stiffness in the analytical and experimental results is noted. The peak of stiffness and strength degradation between the analytical and experimental measurements for the specimens SBCJ-1, SBCJ-2, SBCJ-3 and SBCJ-4 in positive and negative loading directions were 1.00 and 1.11, respectively.

For the seismic responses not only the maximum values should be the same, but also the cyclic hysteretic curves should be similar during the cyclic loading. In the current study, the hysteretic behaviour of the test specimens in terms of beam moment versus rotation and column shear versus drift ratio from both experimental and analytical investigations are presented and detailed discussion are made. A comparison of the beam-column connection is best characterized by its moment versus rotation relation. The hysteretic curves of beam moment versus rotation is shown in Figures 7.1 to 7.4.

7.2 Hysteretic Curves of Beam Moment versus Rotation

Detailed discussion is presented from both experimental and analytical investigations are presented in terms of beam moment versus rotation and column shear versus cyclic loading. In the current study, the hysteretic behaviour of the test specimen, the hysteretic curves should be similar during the cyclic loading. For the seismic responses not only the maximum values should be close to the value of 1.0 for the specimens with floor slab (SBCJ-1) whereas the ratio $M_{\text{Test}} / M_{\text{Ana.}}$ is slightly higher (1.11) for the specimen without slab (SBCJ-1) compared to the specimens with floor slab (SBCJ-2, 3 and 4) (Figures 7.1 to 7.4).
the analytical model to simulate the behaviour of beam-column connection with floor slab well. The comparison of the analytical and experimental results of the beam flexural moment versus beam rotation response for the specimen SBCJ-2, is shown in Figure 7.2. This figure demonstrated a good correlation between the experimental and analytical results and the ratio of $M_{\text{Test}} / M_{\text{Ana.}}$ in both positive and negative directions of cyclic loading were 1.04 and 1.07 respectively.

Hysteretic curves of beam flexural moment versus rotation for specimen SBCJ-3 is shown in Figure 7.3. The floor slab appears to have significant effect on the cyclic behaviour of the beam-column joint, especially in the negative loading direction. The difference between the experimental and analytical results in both positive and negative directions of loading were 1% and 5% respectively.

![Figure 7.1 Hysteretic curves of beam flexural moment vs. rotation for specimen SBCJ-1](image)

Figure 7.1  Hysteretic curves of beam flexural moment vs. rotation for specimen SBCJ-1
Figure 7.2  Hysteretic curves of beam flexural moment vs. rotation for specimen SBCJ-2

Figure 7.3  Hysteretic curves of beam flexural moment vs. rotation for specimen SBCJ-3
Figure 7.4 shows the hysteretic curves of beam flexural moment versus rotation for specimen SBCJ-4. The analytical results demonstrate the prediction accuracy for the proposed approach. It can be seen that the matching between the experimental and analytical results in both positive and negative directions of loading with error less than 7%.

In general, the comparison of the hysteretic curves of the moment-rotation for all the specimens showed a satisfactory agreement between the numerical and experimental results. It can be noted that the analytical models are reasonable in reproducing a similar hysteretic response as the test results, though some differences of reloading stiffness exist. The model can simulate with sufficient accuracy the loss of strength exhibited by some of the structural components.

**Figure 7.4** Hysteretic curves of beam flexural moment vs. rotation for specimen SBCJ-4
7.2.2 **Hysteretic Curves of the Column Shear versus Drift Ratio**

The hysteretic curves in Figures 7.5 to 7.8 show the comparison of column shear versus drift ratio for all the specimens. In these figures the column shear force and the inter-storey drift ratio were calculated for both analytical and experimental measurements based on Eqs. (4.2) and (4.7) respectively.

The simulated hysteretic curves of column shear force versus drift ratio for specimen SBCJ-1 is shown in Figure 7.5. Simulation results demonstrated good predictions for the general behaviour of the subassembly. The hysteretic curves from the experimental and analytical investigations under cyclic loading are similar and at higher loading levels, they closely match each other.

Figure 7.6 shows the comparison results of column shear force versus drift ratio for specimen SBCJ-2. This figure demonstrated the ability of the current model to simulate the cyclic behaviour of beam-column connection with floor slab well and the floor slab increased significantly the column shear demands in both positive and negative directions (approximately by the same amount). The prediction accuracy of the proposed approach with error less than 2% for maximum column shear values in both positive and negative loading directions were demonstrated.

For specimen SBCJ-3, the simulation results of column shear force versus drift ratio is presented in Figure 7.7. It is apparent, that the floor slab effect is more significant on the cyclic behaviour of the beam-column joint in both loading directions. The matching between the experimental and analytical results is quite clear. Nevertheless, obvious matching is existed even during repetition of the same magnitude of the drift cycle in each loading step. The ratio of maximum column shear values $\frac{V_{c\text{ Test}}}{V_{c\text{ Ana.}}}$ were
1.02 and 0.99 in both positive and negative directions of cyclic loading respectively. Similar behaviour was shown for specimens SBCJ-4 (Figure 7.8) with the ratio of maximum column shear values $V_c^{\text{Test}} / V_c^{\text{Ana.}}$ of 1.05 and 1.01, in both directions of cyclic loading respectively. This means that the model is capable to represent the slab-beam-column connection behaviour well.

Generally, it is evident from these figures that the analytical simulation provides positive indications in that the proposed approach can simulate the hysteretic loops of the subassemblies well.

**Figure 7.5** Hysteretic curves of column shear vs. drift ratio for specimen SBCJ-1
Figure 7.6  Hysteretic curves of column shear vs. drift ratio for specimen SBCJ-2

Figure 7.7  Hysteretic curves of column shear vs. drift ratio for specimen SBCJ-3
Figure 7.8  Hysteretic curves of column shear vs. drift ratio for specimen SBCJ-4

The peak points in both positive and negative loading directions were similar during the cyclic loading. They were typical in that they exhibited less pinching effect, and also they showed similar performance in stiffness and strength degradation during repeated drift cycles of the same magnitude. These were attributed to no bond slip through the joint region. As stated earlier in Chapter 3 (Section 3.4.2), all specimens were well designed, and failure is expected due to the beam hinging mechanism. No bond slip losses were noted for the reinforcing bars throughout the joint region, therefore the bond slip loss did not modeled in the current study. However, to accurately evaluate the subassembly behaviour for substandard frame building joints (joints non-codal designed), the cases with bond-slip loss within the joint should be considered.
7.2.3 Hysteretic Curves of the Beam Elongation versus Drift Ratio

The hysteretic curves of the beam elongation versus drift ratio for all the specimens are presented in Figures 7.9 to 7.12.

Figure 7.9 shows the hysteretic curve for the beam elongation versus drift ratio predicted using the developed model (RUAUMOKO result) with the measured values from the experiment as envelope curve (measured envelope) for specimen SBCJ-1. An acceptable agreement between the experimental and analytical results is observed. The maximum beam elongations from the experimental and analytical results were found to be 16.17mm and 12.70mm respectively.

The model can simulate with sufficient accuracy the behaviour of beam elongation/relaxation versus drift ratio with experimental results in case of beam-column subassembly with floor slab, as shown in Figures 7.10 to 7.12.

![Figure 7.9 Beam elongation vs. drift ratio for the specimen SBCJ-1](image)
Figure 7.10  Beam elongation vs. drift ratio for the specimen SBCJ-2

For specimen SBCJ-2, the beam elongations in the model were slightly under estimated for small drift levels as shown in Figure 7.10. However, the measured values were reasonably matching with the predicted values during higher deformation levels, after the crack had started and the multi-spring (Gap) elements started to rock relative to the column. For this specimen, the maximum beam elongations from the experimental and analytical results were found to be 10.02mm and 10.63mm respectively.

Similar behaviour was observed in the specimens SBCJ-3 and SBCJ-4 as shown in Figure 7.11 and 7.12. The maximum beam elongations from the experimental and analytical results for specimen SBCJ-3 were 11.37mm and 10.11mm respectively, while in specimen SBCJ-4 the maximum beam elongations from the experimental and analytical results were found to be 10.48mm and 10.20mm respectively.

Figures 7.9 to 7.12 indicate that the beam elongation increases as the flexural inelastic deformation increases. However, during repetition of the same cycle, with no increase in the flexural deformation, member elongation...
continues to increase. Also the floor slab can significantly reduce this phenomenon, especially at a large deformation levels (drift ratios >1.5%). This effect can be further investigated in the analysis of the multi-connections frame; however, the elongation of the main beams is partially restrained by the exterior columns, which results in axial compression in the main beams.

Figure 7.11  Beam elongation vs. drift ratio for the specimen SBCJ-3

Figure 7.12  Beam elongation vs. drift ratio for the specimen SBCJ-4
7.2.4 Energy Dissipation Capacity

The energy dissipation capacity is a factor of utmost importance, when evaluating the performance of a structure subjected to seismic forces. In general, the comparison of the cumulative energy dissipation capacity for all the specimens showed a satisfactory agreement between the experimental and analytical results, as shown in Figure 7.13.

![Energy Dissipation Capacity Diagram](image-url)

(a) From experimental results

(b) From analytical results

Figure 7.13 Cumulative energy dissipation capacity for all the specimens
However, specimen SBCJ-1 exhibited lesser energy dissipation capacity than the other specimens with floor slabs. For each specimen, the measured and computed cumulative energy dissipation capacity, which contains aspects of both strength and deformation capacity, are relatively the same, confirming that the model works well.

7.3 SUMMARY

In this chapter, a comparison between the experimental results and the analytical results implemented by the nonlinear finite element program RUAUMOKO Software (Carr 2008) was presented.

The results clearly demonstrate the ability of the developed analytical model to simulate the cyclic behaviour of the beam-column connections with and without floor slab with a reasonable calibration for the beam elongation that accompanies with inelastic response of the subassembly. It is also observed that the analytical model improves the prediction of the seismic behaviour and allows the effect of the slab on the joint to be explicitly evaluated, without the complexity of nonlinear Finite Element modelling.