EVALUATION OF SEISMIC IN-PLANE SHEAR DEFORMATION OF GRID-TYPE SYSTEM CEILINGS IN JAPAN

Hirofumi KAMBE1, Tadashi ISHIHARA2, Keigo YAMASHITA3, Kento SUZUKI4, Masayuki NAGANO5

ABSTRACT

Grid-type system ceilings have become widespread in Japan; however, their seismic performance has not been sufficiently investigated yet. The new ceiling standards introduced in 2014 define seismic design procedures for these massive ceilings to validate their strength. However, design procedures for grid-system ceiling are limited because such ceilings cannot maintain their shape during earthquakes owing to their in-plane shear flexibility. Understanding the earthquake resistance properties of grid-system ceilings is therefore essential. This study conducts static loading tests to clarify the in-plane shear capacity of grid-system ceilings in Japan. An analytical model that includes the hysteretic restoring forces is then established based on these test results. Seismic response analysis performed under earthquake conditions shows that the number of stories and ceiling mass can both affect shear deformation. In the analysis, the in-plane shear deformations were larger when tangent-stiffness-proportional damping was used in the ceilings compared with when initial-stiffness-proportional damping was used. The analysis results of all test cases showed that the in-plane shear deformation is approximately 10% of that corresponding to the maximum strength; this means that grid-system ceilings designed in accordance with Japanese industry standards should not be damaged by a moderate earthquake. However, during strong earthquake in-plane shear deformations reach approximately 40% of that corresponding to the maximum strength, they may be severely damaged.

Keywords: Grid-type system ceiling; Conventional steel furring suspend ceiling; Restoring force hysteresis; Wayne-Stewart model

1. INTRODUCTION

Two major types of suspended ceilings are used in Japan: conventional steel furring ceilings and grid-system ceilings (Figure 1). The former comprises panels and steel furring members, as specified by the Japanese Industrial Standard (JIS), whereas the latter comprises standardized T-bars and light panels. Grid-system ceiling is widely used in Japan because of its ease of assembly and layout flexibility.

Figure 1. Two types of suspended ceilings in Japan: grid system (left) and conventional steel furring (right)

1Graduate Student, Tokyo University of Science, Noda, Chiba, Japan, 7113042@alumni.tus.ac.jp
2Senior Research Eng., Building Research Institute, Tsukuba, Ibaraki, Japan, tishihar@kenken.go.jp
3Graduate Student, Tokyo University of Science, Noda, Chiba, Japan, 7113110@alumni.tus.ac.jp
4Assistant Professor, Tokyo University of Science, Noda, Chiba, Japan, suzuki-k@rs.tus.ac.jp
5Professor, Tokyo University of Science, Noda, Chiba, Japan, nagano-m@rs.noda.tus.ac.jp
The Great East Japan Earthquake in 2011 damaged many suspended ceilings and caused them to collapse. Photo 1 shows an example of the disastrous damage caused to a grid-system ceiling during the earthquake (MLIT and BRI, 2012). Before the earthquake, no clear technical standards were laid out for the resistance of suspended ceilings to earthquakes in Japan, except for limited technical advice from the Ministry of Land, Infrastructure, Transport, and Tourism. In light of the damage caused by the earthquake, new standards for ceilings were introduced in 2014 (MLIT, 2013). The new standards defined seismic design procedures for ceilings to validate their strength. However, grid-system ceiling design procedures are limited because such ceilings cannot maintain their shape during earthquakes owing to their in-plane shear flexibility.

The objective of this study is to investigate the seismic responses of grid-system ceilings and their in-plane shear deformation, in particular, focusing on their hysteretic damping and restoring forces. First, the static loading tests are outlined and the results are examined. The test results are then used to establish an analytical model that includes the hysteretic restoring forces. Finally, the seismic responses of grid-system ceilings are evaluated, focusing on in-plane shear deformation. Existing research on the earthquake resistance of ceilings (Ryu et al., 2012) used experimental results to conduct an analysis using mass-spring models, in a similar manner to this study.

2. STATIC LOADING TESTS FOR GRID-TYPE SYSTEM CEILINGS

2.1 Overview

This section outlines the experiments conducted in this study. Figure 2 schematizes the test specimens, whereas Photo 2 shows the experimental specimen. The test specimens included grid-system ceilings from two domestic manufacturers (A and B) and a conventional suspended ceiling using M-bars, as standardized by JIS A6517. Their planar dimensions were $2.4 \times 2.4$ m (16 panels, each $600 \times 600$ mm) for the grid-system ceilings and $3.86 \times 1.82$ m (approximately $7.2$ m$^2$) for the conventional ceiling. The conventional ceiling used 9.5-mm-thick gypsum panels and JIS clips. Table 1 lists the five test specimens used along with the manufacturers and loading directions. For example, in specimen No.1, loading direction is parallel to the main T-bar. Figure 3 shows the different arrangement of T-bars used by different manufacturers. The steel grid of each specimen comprised main T-bars (2400 mm) and cross T-bars (600 mm) for manufacturer A and main T-bars (2400 mm), cross T-bars (1200 mm), and sub-cross T-bars (600 mm) for manufacturer B. Figure 3 also shows ceiling sections for each manufacturer (their T-bar section shapes are slightly different). The panels were dropped into the T-bar grids and were not connected to them.
Table 1. List of test samples.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of Ceiling</th>
<th>Manufacturer</th>
<th>Loading Direction</th>
<th>Ceiling Plenum (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Grid- system suspended ceiling</td>
<td>A</td>
<td>Main T-bar</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cross T-bar</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Conventional suspended ceiling</td>
<td>B</td>
<td>Main T-bar</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cross T-bar</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Conventional suspended ceiling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Conventional suspended ceiling</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Experiment Method and Measurement Points

Figure 4 schematizes the experimental setup considering a grid-system ceiling specimen as an example. Horizontal loading was applied to the center of one end of the specimen to investigate in-plane shear behavior. The grid-system ceilings were braced at both sides for reaction forces and in the perpendicular direction to prevent lateral displacement. For the conventional suspended ceiling, H-shaped steel members were installed on both sides. Measurements were taken at the points shown in Figure 4, wherein the load measured using a load cell and the horizontal displacements were measured using laser measuring devices on independent columns. The targets for laser displacement devices were placed at the three points $d_1$, $d_2$, and $d_3$ (i.e., the center and both sides of the ceiling, as shown in Figures 4(b) and (c)). The shear deformation angle $\gamma$ was obtained as follows:
\[
\gamma = \frac{d_2 - (d_1 + d_3)}{L}
\]

where, \( L \) is the brace interval (1200 mm).

Figure 3. Differences in grid composition and cross section by manufacturer

Figure 4. Frame section and plan schematics showing the loading and measurement points
3. RESULTS OF STATIC LOADING TESTS

3.1 Relation between Shear Force and Shear Deformation Angle

Figure 5 shows the relation between the shear force and shear deformation angle for each specimen. The vertical axes show the in-plane shear force per unit length (kN/m) whereas the horizontal axes show the deformation angle $\gamma$ obtained by Equation 1. The secant stiffness was defined, as in Ishihara et al. (2015), by connecting two points corresponding to approximately 1/2 and 1/3 of the maximum strength capacity, as indicated by the dashed lines in Figure 5.

For all specimens, the hysteresis was peak-oriented during loading and slip-type during unloading, respectively. Regardless of the manufacturer, in-plane stiffness of cross T-bar direction was approximately 17% higher than that of the main T-bar direction, thereby implying that the stiffness of the main T-bar installed orthogonal to the loading direction contributes to the in-plane specimens stiffness of grid-system ceilings. The in-plane stiffness was about 1.7–1.8 times higher in both directions for manufacturer B; this was clearly caused by differences in the manufacturers’ specifications, and the shapes of the T-bar and panel cross sections (Figure 3) may have contributed to this difference.

Table 2 presents the values of in-plane shear stiffness of the specimens with the small stiffness value of specimen No.2 steel grid without the panels, suggesting that the panels significantly contribute to its in-plane shear stiffness. In addition, the table shows that the shear stiffness of a grid-system ceiling is much smaller than that of a conventional suspended ceiling.

![Figure 5](image)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>No.1</th>
<th>No.2</th>
<th>No.3</th>
<th>No.4</th>
<th>No.2 (No Panels)</th>
<th>No.5 (Conventional ceiling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Plane shear stiffness (kN/m)</td>
<td>8.11</td>
<td>9.51</td>
<td>14.35</td>
<td>15.87</td>
<td>0.75</td>
<td>448.90</td>
</tr>
</tbody>
</table>

3.2 Failure Modes

Photo 3 shows the failure modes observed in the experiments. In particular, the most common failures were crushing the panels to separate them from the T-bars (Photo 3(a)) and the T-bars warping (Photo 3(b)). When the load reached approximately 30% of the maximum load, the panels were seen to separate from the T-bars. In-plane shear deformation occurred in all specimens (Photo 3(b)), and some panels eventually fell down from specimen No.1 (Photo 3(c)). During large earthquakes, panels often fall from grid-system ceilings (MLIT and BRI, 2012). Sagging was also observed on the loading side in specimen No.2 (Photo 3(d)).
4. NUMERICAL ANALYSIS OF IN-PLANE SHEAR DEFORMATION IN GRID-SYSTEM CEILINGS

In this section, the in-plane shear deformation of grid-system ceilings during earthquakes is analyzed numerically.

4.1 Input Motion and Analysis Model

The structural frame (shown in Figure 6) was elastic, and the number of stories $n$ was 5, 10, or 15. The model’s primary natural period $T_p$ was set to $0.1n$ (s), and a damping ratio of 5% was assumed as the stiffness-proportional type. As input motions, earthquakes were synthesized using N-S data from the El Centro earthquake to determine the phase characteristics targeting the spectral acceleration ($SA$) set by the Building Standard Law in Japan. Strong earthquake described below is defined as 5 times magnitude of moderate earthquake. For comparison with the moderate earthquake, the structural framework was made linear even during the strong earthquake.

In Figure 7, the black line denotes the $SA$ target and the gray line denotes the acceleration spectra of the synthesized ground motion. The structural response was calculated via time history analysis. Figure 8 shows the floor response spectrum of the top floor acceleration. Herein, the response acceleration at the top of the model was used as the ceiling’s input motion.

Figure 9 shows the ceiling analysis model, which replaces the grid-system ceiling with a multi-mass-spring model. Based on the rules for such ceilings (Rock Wool Association, Japan, 2015), the ceiling model was braced at intervals of 1200 mm for the analysis. The weights of the point masses $m$ in Figure 9 were 1–3 times the actual ceiling’s dead load $d$, assuming equipments were placed on the ceiling. The ceiling model’s parameters were $m$ and the primary natural period $T_1$, which was set to 0.2 and 0.3 s. The brace springs were elastic, and their stiffness $k$ was determined from $T_1$. The spring elements simulated the hysteretic restoring forces obtained in the experiments, which were calculated from specimen No.1’s experimental results. Table 3 provides the stiffnesses $k$ and masses $m$ used. Both tangent-stiffness-proportional and initial-stiffness-proportional damping were considered, with a damping ratio of 3%, to evaluate the effect of the damping type on the response.
Figure 6. Structural model (MDOF)

Figure 7. Response spectrum of input motion (moderate earthquake)

Figure 8. Floor response spectrum (moderate earthquake)

Figure 9. Grid-system ceiling model
Table 3. Stiffness and mass of grid-type system ceiling in calculation

<table>
<thead>
<tr>
<th>Point Mass</th>
<th>(d)</th>
<th>(2d)</th>
<th>(3d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m) (kg)</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>(k) (N/mm)</td>
<td>(T_1 = 0.2s)</td>
<td>7.9</td>
<td>15.79</td>
</tr>
<tr>
<td></td>
<td>(T_1 = 0.3s)</td>
<td>3.51</td>
<td>7.02</td>
</tr>
</tbody>
</table>

4.2 Grid-System Ceiling Hysteresis Model

The experimental results were used to determine suitable parameters for the spring elements shown in Figure 9 so as to simulate the hysteretic restoring forces in grid-system ceilings. The Wayne–Stewart (WS) model (Stewart, 1987) was used to reproduce the hysteretic forces. An outline of this model is shown in Figure 10, and the examples of the parameters used by the model are given in Table 4. The parameters, \(\alpha\), \(\beta\) and \(\gamma\) were changed based on \(K_0\) (the initial stiffness in the WS model) such that the skeleton curve corresponded to the test results. In any cases, \(\eta = 1\) (loading stiffness and unloading stiffness are equal). As in a previous test (Ogihara et al., 2015), the hysteretic restoring force was set to be symmetric about the origin. Figure 11 shows the comparison between incremental analysis results and the test results for different values of \(K_0\). Although the residual displacement in the analysis was slightly larger compared to that used in the experimental results, the slip properties and skeleton curve were broadly similar.

![Image of hysteresis curve of WS model](image-url)

Figures 10 and 11 provide visual comparisons between the model predictions and test results for different values of \(K_0\). The plots illustrate how the shear force and deformation vary with \(K_0\) values, showing a close agreement between the model and experimental data.

![Image of comparison between model and test results](image-url)
Table 4. Examples of WS model parameters.

<table>
<thead>
<tr>
<th>Ko(kN/mm)</th>
<th>A</th>
<th>B</th>
<th>γ</th>
<th>Fc</th>
<th>Fy</th>
<th>μ</th>
<th>π</th>
<th>ξ</th>
<th>ζ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.326</td>
<td>0.226</td>
<td>-0.168</td>
<td>0.01</td>
<td>1</td>
<td>1.7</td>
<td>0.01</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>0.15</td>
<td>0.217</td>
<td>0.151</td>
<td>-0.112</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>0.163</td>
<td>0.113</td>
<td>-0.084</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>0.130</td>
<td>0.090</td>
<td>-0.067</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.30</td>
<td>0.109</td>
<td>0.075</td>
<td>-0.056</td>
<td></td>
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</tbody>
</table>

Same as above

4.3 Analysis Results

Figure 12 and 13 show the results of the moderate earthquake, and Figure 14 shows the result of the strong earthquake.

Figure 12 shows the in-plane shear deformation ratios for the spring elements when $K_0 = 0.2$ kN/mm for different $T_1$ values and damping types. Here, the vertical axes show the ratio of the in-plane shear deformation to the deformation corresponding to the maximum strength recorded in the test (as a percentage), and the horizontal axes show the number of stories and ceiling mass. For $T_1 = 0.2$ s, the maximum in-plane shear deformation reached 5% for tangent-stiffness-proportional damping, whereas the initial-stiffness-proportional damping responses were slightly lower. For $T_1 = 0.3$ s, the responses were a little higher compared with those for $T_1 = 0.2$ s because the ceiling’s natural period was closer to the building’s resonance period; however, the maximum in-plane shear deformation was still less than 10%.

Figure 13 shows the effects of damping type and hysteresis on the in-plane shear deformation for the case wherein the largest response was expected, namely a ceiling mass of $3d$, $T_1 = 0.3$ s, and $n = 5$. The horizontal and vertical axes show $K_0$ and the in-plane shear deformation percentage, respectively. For tangent-stiffness-proportional damping, the in-plane shear deformations increased as $K_0$ increased; however, $K_0$ had little effect when initial-stiffness-proportional damping was used. The maximum in-plane shear deformation shown in Figures 12 and 13 is approximately 15%, suggesting that grid-system ceilings should not be damaged during a moderate earthquake.

Figure 14 also shows the effects of damping type and hysteresis on the in-plane shear deformation for the case wherein the strong earthquake occurs. Ceiling mass of $3d$, $T_1 = 0.2$ s, $K_0 = 0.2$ kN/mm and $n$ ($n=5,10,15$) is a parameter. In this case, the maximum in-plane shear deformation is approximately 40%, grid-system ceilings will be severely damaged during strong earthquake. Considering the test results (section 3.2), panels can be seen to separate from the T-bars. When buildings may be non-linear or, depending on the ceiling natural period etc., there is a risk that the response will be even bigger. There is a possibility panels often fall from grid-system ceilings under strong earthquake.
Figure 12. In-plane shear deformation percentages for the spring elements

Figure 13. Effect of damping type and hysteresis on the in-plane shear deformation percentage

Figure 14. In-plane shear deformation percentages for the spring elements (during strong earthquake)
5. CONCLUSIONS

In this study, the in-plane shear stiffness, shear strength, and failure modes of grid-system ceilings were investigated using static loading tests, and the in-plane shear deformations expected during a moderate earthquake were evaluated numerically. The conclusions can be summarized as follows.

(1) The in-plane shear stiffness and capacity of grid-system ceilings are much smaller than those of conventional Japanese steel furring ceilings.

(2) Two general types of failure modes were observed: panel collapse caused by compression and large in-plane shear deformations of the grid accompanied by T-bar warping.

(3) An analytical model based on the Wayne–Stewart model was used to reproduce the hysteretic restoring forces in grid-system ceilings. Seismic response analyses showed that they are unlikely to be damaged by in-plane shear deformations during a moderate earthquake. When tangent-stiffness-proportional damping is used in such ceilings, the in-plane shear deformations increase with the \( K_0 \) used to characterize the restoring forces; however, this stiffness has little effect when initial-stiffness proportional damping is used.

(4) During the strong earthquake, the maximum in-plane shear deformation is approximately 40%, suggesting that grid-system ceilings will be severely damaged during strong earthquake. Panels can be seen to separate from the T-bars under strong earthquake.

6. ACKNOWLEDGMENTS

The authors are grateful to Mr. Shinsuke Inai (Toda Construction Co., Ltd.) for technical advice on the experiments.

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