MECHANICAL PROPERTIES AND REQUIRED SEISMIC DEFORMATIONS OF STEP PARTS IN STEEL-FURRING SUSPENDED-CEILING SYSTEMS IN JAPAN

Keigo YAMASHITA 1, Tadashi ISHIHARA2, Hirofumi KAMBE3, Kento SUZUKI4, Masayuki NAGANO5

ABSTRACT

The recent Japanese standard for ceilings recommends that adjacent ceiling zones be separated at the step part to avoid earthquake damage. If step parts are integrated, small deformations by the required bracings may not cause damage. To clarify the conditions under which damage to conventional continuous step parts can be prevented, a better understanding of the mechanical properties and required seismic deformations of the step parts of steel furring suspended ceiling systems is necessary. In this study, static loading tests were conducted to investigate the mechanical properties of the step parts of steel furring suspended ceiling systems. Allowable deformations were determined for the step parts and compared with the forced deformation during an earthquake, estimated using numerical analysis. Time history analyses demonstrated that the forced deformation of the step parts exceeded the allowable deformation only when the ceiling was installed in a building with a relatively short natural period. They did not exceed the allowable limits when the difference in natural periods between the adjacent ceiling zones across the step part was small. The forced deformations were also calculated using the response-spectrum method and compared with those obtained using time history analysis. The deformations calculated using the response-spectrum method were larger than those calculated using time history analysis.

Keywords: Steel furring suspended ceiling system; Specified ceiling; Step part; Static loading test; Time history analysis

1. INTRODUCTION

Recently, the collapse of large suspended ceilings during seismic events has attracted attention. In the Great East Japan Earthquake of 2011, many suspended ceilings suffered damage and collapsed. As a result, improved standards for ceilings were introduced in 2014 (Ministry of Land, Infrastructure, Transport and Tourism, 2013). The new standard recommends separating adjacent ceiling zones across step parts. Although conventional continuous step parts may not be damaged by bracing, their capacity to resist earthquakes requires clarification. In this study, static loading tests were conducted to clarify the mechanical properties of the step parts of a steel furring suspended ceiling system. The forced deformations were calculated using numerical analysis and compared with experimental data. The forced deformations were also calculated using the response-spectrum method and compared with those obtained when time history analysis was used.

1Graduate Student, Tokyo Univ. of Science, Noda, Chiba, Japan, 7113110@alumni.tus.ac.jp
2Senior Research Engineer, Building Research Institute, Tsukuba, Ibaraki, Japan, tishihar@kenken.go.jp
3Graduate Student, Tokyo Univ. of Science, Noda, Chiba, Japan, 7113042@alumni.tus.ac.jp
4Assistant Prof., Tokyo Univ. of Science, Dr. Eng., Noda, Chiba, Japan, suzuki-k@rs.tus.ac.jp
5Prof., Tokyo Univ. of Science, Dr. Eng., Noda, Chiba, Japan, nagano-m@rs.noda.tus.ac.jp
2. EXPERIMENTAL SETUP

2.1 Specimens

The specimen used in the experiment is shown in Figure 1, and its specifications are summarized in Table 1. The experimental setup is shown in Photo 1. The test specimen was a steel furring suspended ceiling system, using steel bars and boards based on the standard of the Japan Industry Standard (JIS). The key parameter was the horizontal force applied to the step part. Two test specimen types were used: compression specimens (“compression”) and shear specimens (“shear”). Other test parameters were the direction of steel furring, the specification of the step part, the clip type, and the thickness of the gypsum board. Specimens comprised 300-mm-high step parts. To ensure that the force acted only on the board, the steel furring was separated by 20 mm inside the ceiling edge (Photo 1(a)). Figure 2 shows the three specifications of diagonal reinforcement used. That shown in Figure 2(a) was of the C bar type; in Figure 2(b), the C-shaped steel type on the C bar and in Figure 2(c), the single M bar type with stud (WS-65). Three diagonal reinforcements were used in a compression specimen and eight in a shear specimen, following the standards of the Public Building Association, 2016. The stud was fastened to the M bar and gypsum board (Photo 2). Two types of clip were used: JIS standard compliant and wind resistant. To investigate the influence of board thickness on the stiffness and strength of the step part, two types of gypsum board with thicknesses of 9.5 and 12.5 mm were tested. Figure 3 shows the names given to the specimens used in the experiments.

![Figure 1. Outline of the specimen](image-url)
2.2. Static Loading Experiment: Method and Measurement Points

Figure 4 shows the experimental method and measurement points. In the static loading test, both ends of the suspended ceiling were attached to H-shaped steel as beams for the acting and reaction forces. The ceiling was compressed from one end in the horizontal direction, and the other end was fixed. In this experiment, loading and unloading were applied only in compression. No tensile loading was applied. Laser deformation sensors were set horizontally at the two ends of each specimen. A load cell was installed between the force jack and the load beam.
Using Equation (1), the deformation $d_O$ of the whole test specimen was calculated from the difference between the average deformation $d_F$ at the applied force side and the average deformation $d_R$ at the reaction force side. Positive $d_O$ was assumed to be the direction of shrinkage of the test specimen. The deformation of the step part was measured at three points in the upper and lower boards, using laser deformation sensors installed on the pillar. The deformation $d_S$ was calculated using Equation (2) from the difference between the average deformation $d_U$ at the upper board and $d_D$ at the lower board, the step height $L$ (300 mm), and the height measurement point $b$ (50 mm).

\[
d_O = d_F - d_R \tag{1}
\]

\[
d_S = \frac{(d_U - d_D)L}{L - 2 \times b} \tag{2}
\]

3. EXPERIMENTAL RESULTS

3.1. Relationship Between Load and Deformation

Figure 5 shows the relationship between the force and deformation for each specimen. The force was normalized by dividing the specimen width (compression: 1.82 m, shear: 2.55 m × 2) to obtain a force per unit length. The solid and open triangles in Figure 5 show the allowable deformation, defined as half deformation at the maximum capacity.

The upper part of Figure 5 compares the results by the direction of steel furring. Results from the compression tests are shown in Figures 5(a-1) and (a-2). In the C bar direction (CC), the stiffness of the step parts, the deformation at the maximum capacity, and the allowable deformations were all greater than those in the M bar direction (CM). No significant difference was found in the deformation at maximum capacity of the two board thicknesses. As shown in Figure 5(b), the shearing stiffness of the step parts and the deformation maximum capacity were smaller than the compression, and the allowable deformation was large.

Figure 4. Loading and measurement points
Figure 5. Relationship between force and deformation of the specimen

Table 2. Experimental results

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen</th>
<th>Deformation at maximum capacity (mm)</th>
<th>Allowable deformations (mm)</th>
<th>Stiffness of specimen (kN/mm/m)</th>
<th>Stiffness of the ceiling without step part (kN/mm/m)</th>
<th>Deformation at maximum capacity (mm)</th>
<th>Allowable deformations (mm)</th>
<th>Stiffness of step part (kN/mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CC1J9</td>
<td>49.65</td>
<td>17.30</td>
<td>0.103</td>
<td>2.96**</td>
<td>29.10</td>
<td>9.60</td>
<td>0.092</td>
</tr>
<tr>
<td>2</td>
<td>CC1J12</td>
<td>44.03</td>
<td>22.41</td>
<td>0.095</td>
<td>-</td>
<td>29.50</td>
<td>10.40</td>
<td>0.180</td>
</tr>
<tr>
<td>3</td>
<td>CC1B12</td>
<td>37.97</td>
<td>8.49</td>
<td>0.180</td>
<td>-</td>
<td>29.70</td>
<td>6.70</td>
<td>0.080</td>
</tr>
<tr>
<td>4</td>
<td>CM2J9</td>
<td>17.18</td>
<td>6.95</td>
<td>0.080</td>
<td>2.22**</td>
<td>10.60</td>
<td>3.45</td>
<td>0.080</td>
</tr>
<tr>
<td>5</td>
<td>CM2J12</td>
<td>13.62</td>
<td>4.82</td>
<td>0.177</td>
<td>-</td>
<td>6.50</td>
<td>2.10</td>
<td>0.150</td>
</tr>
<tr>
<td>6</td>
<td>CM3J12</td>
<td>47.72</td>
<td>12.64</td>
<td>0.021</td>
<td>-</td>
<td>57.10</td>
<td>14.20</td>
<td>0.020</td>
</tr>
<tr>
<td>7</td>
<td>SC1J9</td>
<td>57.40</td>
<td>36.94</td>
<td>0.004</td>
<td>-</td>
<td>54.70</td>
<td>35.40</td>
<td>0.004</td>
</tr>
<tr>
<td>8</td>
<td>SM2J9</td>
<td>174.94</td>
<td>67.83</td>
<td>0.010</td>
<td>0.55**</td>
<td>204.17</td>
<td>65.10</td>
<td>0.010</td>
</tr>
</tbody>
</table>

※ 1 Value calculated from the load deformation relationship per unit width measured at the step part
※ 2 Allowable deformation defined as a deformation equivalent to 1/2 of the maximum capacity
※ 3 Secant stiffness connecting two points corresponding to about 1/3 to about 1/2 of the maximum capacity
※ 4 Specimen length: 3850 mm
※ 5 Stiffness of shear span from in-plane shear test: 910 mm (Kambe et al., 2017)

Figure 5(c) compares the results for different specifications of the step part. There was little difference in maximum capacity between CM2 and CM3 specimens. Although the latter had less stiffness in the step parts, the allowable deformation was large.

Figure 5(d) compares specimens with different clip types. The wind-resistant clip produced greater stiffness in the step parts and a larger maximum capacity than the JIS clip. Conversely, the deformation at the maximum capacity and the allowable deformation were smaller when using the wind-resistant clip. The use of a wind-resistant clip makes lateral sliding more difficult, as the C bar and M bar are hard coupled.

Figure 5(e) shows the effect of the step part. Data on a ceiling without a step part were taken from Inai et al. (2015). The step parts had significantly lower stiffness, and the maximum capacity was much smaller than that of the ceiling without steps.

Table 2 summarizes the full test results, including the deformation and stiffness of the whole specimen and of the step part. No difference was found in the stiffness of the whole specimen and the stiffness of the step part, suggesting that the stiffness of the step part determines the stiffness of the whole.
3.2. Failure Modes

Photo 3 shows the failure modes of the different specimens. Photo 3(a) shows compressive failure of the boards due to slipping of the clip. Photo 3(b) shows torsional deformation in the C bar due to flexural bending of the ceiling as the clip disengages. Photo 3(c) shows cracking of the boards due to bending of the ceiling. Photo 3(d) shows cracks in the boards of the step part. Photo 3(e) shows pull-out of screws. Photo 3(f) shows tilt of the C bar. Torsional in the C bar and deformation of the hanger bolt were observed in all specimens. Flexural bending caused the clip to disengage from the ceiling surface and introduced torsional of the C bar. Compressive failure of the boards due to slippage of the clip was observed only in specimen CC1J, where the JIS clip was applied.

Under compression, failure occurred at different places, depending on the direction of the steel furring. At the lower part of the ceiling, bending failure was observed in the direction of the C bar (CC). In contrast, board cracking and pull-out of screws at the step part occurred in the direction of the M bar (CM).

4. ESTIMATION OF DEFORMATION CAPACITY REQUIRED DURING EARTHQUAKES AND SEISMIC PERFORMANCE

The forced deformation of the step parts under earthquake conditions was estimated using numerical methods. The seismic performance of the step part was measured against the allowable deformation.

4.1 Input Motion and Analysis Model

Figure 6 shows the structure model used to calculate the input motion to the ceiling. This was a multi-mass model with constant mass. The number of stories \( n \) ranged from 3 to 15. The primary natural period \( T_1 \) was set to \( T_1 = 0.1 \) (s), and the stiffness of each story was set such that the first modal shape was an inverted triangular mode. The damping ratio of 5% was set for the first mode as the stiffness proportional type. Figure 7 shows the ceiling model used to analyze forced deformation in the presence of step parts. This was a spring-mass model, in which the brace and ceiling were represented by springs and masses.
The left and right ceilings were set as separate single-degree-of-freedom systems. The natural period of one ceiling was fixed to 0.2 s, and the natural period of the other was varied in a range from 0.21 to 0.30 s. As the stiffness of the step part was assumed to be significantly smaller than that of the ceiling in the experiments (Table 1), the spring representing the step part was ignored. The attenuation of the ceiling depends on its type and specification (Japan Building Disaster Prevention Association, 2012, Okuda et al., 2012), 5% damping was assumed as the average value.

Figure 8 shows the acceleration time history used as the input motion to the building model. Input motions were set to match the target spectrum shown by black lines in Figure 9. The earthquake motion input to the building model replicated the acceleration response spectrum of the second ground type in the Building Standard Law (region coefficient $Z = 1.0$). The phase characteristics were based on three recorded motions: The El Centro NS wave, Hachinohe NS wave, and Taft EW wave. The analysis parameters were the number of stories, the natural period of the ceiling, and the difference in natural period between the two ceilings. The peak relative deformation between the two single-degree-of-freedom systems in the ceiling model represented the forced deformation capacity in the step part.
4.2. CQC Methods

The forced deformations were also calculated using the complete quadratic combination (CQC) method, and the results were compared with those obtained using time history analysis. The CQC method (SPD method Kasai and Binh (2004)) by Equations (3) and (4) was used as a response-spectrum method. The results were validated by comparison with those calculated using the time history response.

\[
u = \sqrt{u_A^2 + u_B^2 - 2\rho_{CQC}u_Au_B}
\]

\[
\rho_{CQC} = \frac{8h_Ah_B\left(h_B + \frac{T_B}{T_A}\right)^{1.5}}{\left[1 - \left(\frac{T_B}{T_A}\right)^2\right]^2 + 4h_Ah_B\left(1 + \left(\frac{T_B}{T_A}\right)^2\right)\frac{T_B}{T_A} + 4(h_B^2 + h_A^2)\left(\frac{T_B}{T_A}\right)^2}
\]

where \(u_A\) and \(u_B\) are the maximum response values of the two ceilings, \(h_A\) and \(h_B\) are the damping ratios, and \(T_A\) and \(T_B\) are the natural periods \((T_A \geq T_B)\). \(u\) is the maximum forced deformation by the CQC method.

4.3. Evaluation of Maximum Forced Deformation

Figure 10(a) shows the maximum forced deformation at the top story of the building, calculated using time history analysis. The vertical axis represents the maximum forced deformation, and the horizontal axis represents a combination of the number of stories in the building model and the natural period in the ceiling model. In Figure 10, colors other than orange represent cases that fell within the allowable deformation (Table 2) for the step part of compression No. 1 (direction of the C bar) and No. 4 (direction of the M bar). When the primary natural period of the building was short and the natural period difference of the ceiling was long, the maximum forced deformation exceeded the allowable deformation. In more than half of all cases, the maximum forced deformation fell within 9.60 mm, corresponding to the allowable deformation of No. 1. The allowable deformation of shear (Nos. 7 and 8) is larger than that of No. 1 so that most cases were below the allowable shear deformation. These
results suggest that separation of the step parts of the ceiling may be unnecessary when the building has a relatively long primary natural period or when the natural period difference between the ceilings on the both sides of the step is small.

Figure 10(b) shows the maximum forced deformation at the top story, calculated using the response-spectrum method. The overall trend in maximum forced deformation was similar to the results using the time history analysis, though the CQC method gave larger values. Figure 11 compares the correlation coefficient $\rho_{CQC}$ calculated by Equation (4) with the coefficient $\rho_{THA}$ calculated by Equation (5), based on the time history analysis in the El Centro NS wave.

$$\rho_{THA} = \frac{u_{THA}^2 - u_A^2 - u_B^2}{-2u_Au_B} \quad (5)$$

where $u_{THA}$ is the maximum forced deformation calculated by time history analysis and $\rho_{THA}$ is the corresponding correlation coefficient.

The vertical axis is the correlation coefficient, and the horizontal axis is the natural period of the ceiling. $\rho_{CQC}$ approached $\rho_{THA}$ as the natural period difference of the ceilings became smaller and the number of building stories was reduced. $\rho_{THA}$ was close to 1.0 in many cases. When $\rho_{THA} \approx 1.0$, $u \approx |u_A - u_B|$. This reflects a simple difference in maximum response values, suggesting that the two ceilings vibrate almost in phase. The large difference in the correlation coefficients from the CQC method and the time history response were attributed in part to the strong influence of building structural responses on the input motion to the ceiling.

5. CONCLUSIONS

The conclusions of the study are as follows:

(1) The mechanical properties of the step parts were clarified by static loading tests. The observed failure modes were bending of the ceiling, cracking of the boards, and pulling-out of screws.

(2) The forced deformation of step parts under earthquake conditions exceeded the allowable deformation only when the ceiling was installed in a building with a relatively short natural period. The forced deformation may not exceed the allowable limit when the difference between the natural periods of adjacent ceiling zones across the step part was small. Step parts can therefore be integrated by appropriate selection of the natural period of the building and the adjacent ceiling zones.

(3) Forcde deformation of step parts under earthquake conditions was estimated using two approaches: the response-spectrum method and time history analysis. The forced deformation calculated by the response-spectrum method was larger than that obtained using time history analysis.
6. ACKNOWLEDGMENTS

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7. REFERENCES


Ministry of Land, Infrastructure, Transport and Tourism (2013). Establishment of specified ceiling and a construction method that is effective for structural resistance of specified ceiling, August (in Japanese)


