Comparison of buckling load for H-shaped compression members with different eccentric bracing methods

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Abstract

In Japanese design code, the bracing for the compression members is supported to be set up on the centroid of its section. On the other hand, the braces may be not jointed at the centroid for the compression members in the real structures, and be eccentrically jointed on the section of members. If non-structural members are used as bracings, it is more effective to design the space frame. These members are supported to be effective to restrain the buckling deformation for the compression members, and then most of non-structural members are plurally or continuously jointed. Our previous papers have evaluated the effect of the eccentric braces to restrain the buckling deformation for H-shaped compression members with an eccentric brace at the center of the member, and with continuously eccentric braces, respectively. But the effect for the continuously eccentric braces may be different from that for an eccentric brace at the center of the compression member. If it makes the effect of each eccentric bracing equivalent, it is more practical to design the compression members with eccentric braces in the space structures.

This paper compares the elasto-plastic buckling behavior for H-shaped compression members with eccentric braces at the center of members to that with continuously eccentric braces, and suggests the unified estimation method for the effect of the buckling restraint for each eccentric bracing.
1 Elastic buckling load for H-shaped compression members with different eccentric braces

1.1 Development of elastic buckling load for H-shaped compression members with eccentric different braces

In this section, the elastic buckling load for H-shaped compression members with eccentric braces is developed by the energy method and the eigen-value analyses.

When an H-shaped compression member with eccentric brace is laterally and torsionally buckled, the potential energy $U$ is expressed as the following in reference to Kimura.

Then the flexural and torsional buckling deformation with web distortion occurs as shown in Fig. 1 (Bleich [3]).

$$U = \frac{1}{2} \int_0^l \left[ EI_1 u_1'^2 + EI_2 u_2'^2 + GK_1 \beta'^2 + GK_1 (\beta' - \alpha'_1)^2 + GK_2 (\beta' - \alpha'_2)^2 
+ \frac{4D_w}{d} (\alpha_1^2 + \alpha_2^2 + \alpha_z^2) - P_1 u_1'^2 - P_2 u_2'^2 \right] dx 
+ \frac{1}{2} \left[ \lambda K_{\beta} (\beta - \alpha_1)^2 \bigg|_{x=\frac{l}{2}} + \lambda K_{u_0} u_0^2 \bigg|_{x=\frac{l}{2}} \right]$$ (1)

where $EI_i$ is the flexural rigidity of each flange for H-shaped member, $GK_i$ is the torsional rigidity of each flange and $GK_w$ is the torsional rigidity of web. $D_w$ is the flexural rigidity of web plate for H-shaped members. $D_{uw}$ is the lateral rigidity of the brace and $\lambda K_{\beta}$ is the rotational rigidity of the brace. $d$ is the distance between both flanges and $l$ is the length of H-shaped members. $P_i$ and $u_i$ are the compression load and the lateral displacement at the center of the flanges, $u_0$ is the lateral displacement at the brace point. $\beta$ is the torsional angle, and $\alpha_i$ is the rotational angles of each flange due to web distortion. The suffix, $i$, represents 1 and 2, and it means each flange.

![Buckling Deformation for Compression Members](image1)

![Bracing Models and Buckling Deformation of Section](image2)

**Figure 1:** Buckling deformation for H-shaped compression members with eccentric braces (Type A).
In this paper, it is constantly assumed that the cross section of H-shaped member is symmetric, then $EI_1=EI_2=EI_f$, $GK_1=GK_2= GK_f$ and $P_1=P_2=P_f$. Then it is also assumed that braces are set up at upper flange, so $u_0$ is equal to $u_1$. The ratio of eccentric distance to web depth, $e/h$, is equal to 0.5. Web deformation is expressed in the deflection curve with $\alpha_1$ and $\alpha_2$.

$$w = \frac{s(s-d)^2}{d^2} \alpha_1 + \frac{s^2 (s-d)}{d^2} \alpha_2$$

(2)

The boundary condition is simple support to strong and weak axis. Lateral deformation of member and web deformation are expressed in the function of sine curves in the following

$$u_1 = a_1 \sin \frac{\pi}{l} x + a_2 \sin \frac{2\pi}{l} x , \quad u_2 = b_1 \sin \frac{\pi}{l} x + b_2 \sin \frac{2\pi}{l} x$$

$$\alpha_1 = c_1 \sin \frac{\pi}{l} x + c_2 \sin \frac{2\pi}{l} x , \quad \alpha_2 = d_1 \sin \frac{\pi}{l} x + d_2 \sin \frac{2\pi}{l} x$$

(3)

Torsional angle, $\beta$, is expressed with the lateral deformation of flanges, $u_1$ and $u_2$ as the following

$$\beta = \frac{u_2 - u_1}{d}$$

(4)

The lateral deformation, $u_1$ and $u_2$ at the center of the member are expressed with the eccentric distance, $e$ and the torsional angle, $\beta_0$.

$$u_1 = (e - \frac{d}{2}) \beta_0 \quad , \quad u_2 = (e + \frac{d}{2}) \beta_0 \quad , \quad u_1 = (e - \frac{d}{2}) \beta_0 \quad , \quad u_2 = (e + \frac{d}{2}) \beta_0$$

(5)

The relationship between the lateral deformation, $u_1$ and $u_2$ is obtained from Eqs. (4) and (5) as the following.

$$u_1 = \frac{2e-d}{2e+d} u_2 \quad u_1 = \frac{2e-d}{2e+d} u_2$$

(6)

In this paper, the eccentric distance $e$ in the range of $e \geq d/2$ is adopted. Substituting Eq. (6) for Eq. (1), the buckling load $P_{cr}$ is obtained as the following

$$P_{cr} = EI_y \left( \frac{\pi}{l} \right)^2 + 2 \frac{d^2}{d^2} \{ GK_w + (\tau_1 + \tau_2) GK_f + \tau_1 \frac{2A K_\mu}{l} \left( \frac{l}{\pi} \right)^2 \} + 2 \frac{d^2}{d^2} \{ A K_u \left( \frac{l}{\pi} \right)^2 \}$$

$$- \sqrt{ \frac{2}{d^2} \{ GK_w + (\tau_1 + \tau_2) GK_f + \tau_1 \frac{2A K_\mu}{l} \left( \frac{l}{\pi} \right)^2 \} + 2 \frac{d^2}{d^2} \{ A K_u \left( \frac{l}{\pi} \right)^2 \}^2$$

$$P_{cr} = 4EI_y \left( \frac{\pi}{l} \right)^2$$

(7)

(8)

where $P_{cr}=2P_f$ and $EI_y=2EI_f$, $\tau_1$ is the reduction of the rotational rigidity and the upper flange torsional rigidity, and $\tau_2$ is the reduction of the lower flange torsional rigidity. Where $l_b$ is the buckling length. Eq. (7) is the equation for the flexural-torsional buckling load with web deformation. Eq. (8) is the equation for
Euler’s buckling load for \( l_b = l/2 \). Where, the relationship between the torsional angle \( \beta_0 \) and the rotational angle of each flange \( \alpha_1 \) and \( \alpha_2 \) is expressed with \( \tau_1 \) and \( \tau_2 \).

\[
\beta_0 - \alpha_1 = \tau_1 \beta_0, \quad \beta_0 - \alpha_2 = \tau_2 \beta_0
\]

(9)

\( \tau_1 \) and \( \tau_2 \) are obtained from Eq. (9) as the following

\[
\tau_1 = \frac{6D_w}{d} \left\{ \frac{GK_f}{l} \left( \frac{\pi}{l} \right)^2 + \frac{2D_w}{d} \right\} \left\{ \frac{GK_f}{l} \left( \frac{\pi}{l} \right)^2 + \frac{4D_w}{d} \right\} - \frac{2D_w}{d} \right\} \left\{ \frac{GK_f}{l} \left( \frac{\pi}{l} \right)^2 + \frac{4D_w}{d} \right\} - \frac{2D_w}{d} \right\}
\]

(10)

\[
\tau_2 = \frac{6D_w}{d} \left\{ \frac{GK_f}{l} \left( \frac{\pi}{l} \right)^2 + \frac{2D_w}{d} \right\} \left\{ \frac{GK_f}{l} \left( \frac{\pi}{l} \right)^2 + \frac{2K\pi}{l} \right\} \left\{ \frac{GK_f}{l} \left( \frac{\pi}{l} \right)^2 + \frac{4D_w}{d} \right\} - \frac{2D_w}{d} \right\}
\]

(11)

The smaller value of \( P_{cr} \) obtained from Eqs. (7) and (8) can be used as the buckling load for H-shaped compression members with eccentric braces. Similarly, elastic buckling load for H-shaped compression members with continuously eccentric braces is obtained by the energy method and the eigenvalue analyses. When H-shaped compression member with continuously eccentric brace is laterally and torsionally buckled, the potential energy \( U \) is expressed as the following in reference to Kimura and Amamoto [2].

Then the flexural and torsional buckling deformation with the web distortion occurs as shown in Fig. 2 (Bleich [3]).

\[
U = \frac{1}{2} \int_0^l \left[ EI_1 u_1''^2 + EI_2 u_2''^2 + G K_w \beta ^2 + G K_1 (\beta' - \alpha_1')^2 + G K_2 (\beta' - \alpha_2')^2 \right. \\
+ \frac{4D_w}{d} (\alpha_1^2 + \alpha_2^2 + \alpha_2^2) - P_1 u_1'' - P_2 u_2'' \right] \, dx + \frac{1}{2} \left\{ b K_\beta (\beta - \alpha_1)^2 + b K_\beta u_0'' \right\}
\]

\[
\alpha_1 = b K_\alpha l, \quad \alpha_2 = b K_\beta l
\]

(12)

Figure 2: Buckling deformation for H-shaped compression members with continuously eccentric braces (Type B).
Then it is defined that the case of the rigidity multiplied by length of members in eq. (13) is equivalent to the bracing rigidity for the case of eccentric braces at the center of members as Eqs. Lateral deformation of member and web deformation are expressed in the function of sine curves in the following

\[ u_0 = u_1 = a_1 \sin \frac{n\pi}{l} x, \quad u_2 = a_2 \sin \frac{n\pi}{l} x \]

\[ \alpha_1 = b_1 \sin \frac{n\pi}{l} x, \quad \alpha_2 = b_2 \sin \frac{n\pi}{l} x \] (14)

Substituting Eq. (6), (14) for Eq. (12), the buckling load \( P_{cr} \) is obtained as the following

\[
P_{cr} = EI_y \left( \frac{n\pi}{l} \right)^2 + \frac{2}{d^2} \{GK_w + (\tau_1 + \tau_2)GK_f + \tau_1 bK_{\beta} \left( \frac{l}{n\pi} \right)^2 \} + B K_u \left( \frac{l}{n\pi} \right)^2 \]

\[ -\sqrt{\left( \frac{2}{d^2} \{GK_w + (\tau_1 + \tau_2)GK_f + \tau_1 bK_{\beta} \left( \frac{l}{n\pi} \right)^2 \} + B K_u \left( \frac{l}{n\pi} \right)^2 \right)^2} \] (15)

The buckling load for H-shaped compression members with continuously eccentric braces is obtained from Eq. (15), with the order of buckling mode, \( n \), for the lowest buckling load in this equation. Eq. (15) is the equation for the flexural-torsional buckling load with web deformation. \( \tau_1 \) and \( \tau_2 \) is obtained from Eq. (9) as the following

\[
\tau_1 = \frac{6D_w}{d} \left\{ GK_f \left( \frac{n\pi}{l} \right)^2 + \frac{2D_w}{d} \right\} \left\{ GK_f \left( \frac{n\pi}{l} \right)^2 + \frac{4D_w}{d} + bK_{\beta} \right\} \left\{ GK_f \left( \frac{n\pi}{l} \right)^2 + \frac{4D_w}{d} \right\} - \left( \frac{2D_w}{d} \right)^2 \] (16)

\[
\tau_2 = \frac{6D_w}{d} \left\{ GK_f \left( \frac{n\pi}{l} \right)^2 + \frac{2D_w}{d} + bK_{\beta} \right\} \left\{ GK_f \left( \frac{n\pi}{l} \right)^2 + \frac{4D_w}{d} \right\} - \left( \frac{2D_w}{d} \right)^2 \] (17)

Fig. 3 shows the numerical analysis model for the H-shaped compression members with eccentric brace. Marc 2008 is used for the numerical analyses. Type A represents the eccentrically braced members at the center of structural members, and Type B represents structural members with continuously eccentric braces. The compression member consists of 4 node shell elements, and the eccentric brace is replaced on the lateral and rotational springs. In Type B, The spacing between bracings, \( l' \), is equal to 250 mm. Then the value of lateral and rotational rigidity of springs are calculated as \( bK_{\alpha}l' \) and \( bK_{\beta}l' \), respectively. The boundary condition is simple supports to strong and weak axis, and three kinds of the cross-sectional shapes are adopted as shown in Table 1.
Figure 3: Numerical analysis models.

Table 1: Cross-sectional shape of H-shaped members.

<table>
<thead>
<tr>
<th>b/h</th>
<th>h</th>
<th>b</th>
<th>t_w</th>
<th>t_f</th>
<th>(mm)</th>
</tr>
</thead>
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<tr>
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<td>300</td>
<td>150</td>
<td>6.5</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>0.68</td>
<td>294</td>
<td>200</td>
<td>8</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>300</td>
<td>300</td>
<td>10</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

1.2 Comparison of equivalent bracing rigidity for H-shaped compression members with different eccentric braces

Fig. 4 shows the relationship between the elastic buckling stress, $\sigma_{cr}$, for H-shaped compression members with eccentric braces and slenderness ratio, $\lambda$.

Figure 4: Elastic buckling stress for H-shaped compression members with eccentric braces.
The buckling load for H-shaped compression members with eccentric braces (in Type A) is obtained from Eqs. (8) and (9), and the smaller value of $P_{cr}$ obtained from both expressions, is used. The buckling load for the case of continuously eccentric braces (in Type B) is obtained from Eq. (16). For the small slenderness ratio, if bracing rigidity in Type A is equal to that in Type B, $A K_u = B K_u$, $A K_\beta = B K_\beta$, the elastic buckling stress in Type A is constantly higher than that in Type B. In this case, the buckling stress for Type A is equal that for Type B when the lateral and rotational rigidity of Type A ($K_u, K_\beta$) is in half of that for Type B ($b K_u = 0.5 A K_u, b K_\beta = 0.5 A K_\beta$), respectively. In addition, the buckling stress for Type B with $n = 2$ is constantly higher than that for perfect support for Type A. Then the plots $\nabla$, $\triangledown$ in Fig. 4 are the points to change from the lateral-torsional buckling to Euler’s Buckling for $l_b = l/2$ in Type A, and $\nabla$ in Fig. 4 is the point to change from the buckling load for $n = 1$ to buckling load for $n = 2$ in Type B.

Fig. 5 shows the relationship between the lateral rigidity ratio, $A K_u / A l$, for Type A and that, $b K_u / b l$, for Type B, when the bucking mode changes such as the plots, $\nabla$, $\triangledown$ and $\nabla$ in Fig. 4.

$A K_u / A l$, and $b K_u / b l$, are expressed as the ratio of the lateral rigidity to length for Type A and for Type B. The parameter is the cross-sectional shape. The lateral rigidity ratio for Type B, $b K_u / b l$, is constantly higher than that for Type A, $A K_u / A l$. It is shown that wide flange, $b / h = 1.0$, requires the higher rigidity, $A K_u / A l$ than the other at the same $b K_u / b l$.

Figure 5: Comparison of lateral rigidities between Type A and Type B.

Figure 6: Initial impressions.
2 Evaluation of elasto-plastic buckling stress for H-shaped compression members with different eccentric bracings

2.1 Elasto-plastic buckling behavior for H-shaped compression members with different eccentric bracings

In this section, elasto-plastic buckling behavior for H-shaped compression members with eccentric braces at the center of the members and with continuously eccentric braces is confirmed by the elasto-plastic large deformation analyses. Marc version 2008 is used [MSC, 2008]. The analyses models and boundary condition are same as the eigen-value analyses models in the previous section. Material properties for H-shaped members are shown in Table 2. Initial impressions of the lateral displacement, \( u \), the torsional angle, \( \beta \), and the rotational angle of each flange due to the web distortions, \( \alpha_i \), are described as the function of sine curves in the followings.

\[
\begin{align*}
u &= \frac{l}{2500} \sin \frac{\pi x}{l} + \frac{l}{10000} \sin \frac{2\pi x}{l} \\
\beta &= \tan^{-1}(u/d) \\
\alpha_i &= \tan^{-1}(u/d)
\end{align*}
\]

where the suffix \( i \) represents 1 and 2, and it means each flange. The web distortion is expressed in the deflection curve with \( \alpha_1 \) and \( \alpha_2 \) as the following.

| Table 2: Material properties of H-shaped members. |
|---|---|---|---|
| \( E \) (kN/mm\(^2\)) | \( E_{ult} \) (kN/mm\(^2\)) | \( \sigma_t \) (N/mm\(^2\)) | \( \sigma_u \) (N/mm\(^2\)) |
| 206 | 2.74 | 294 | 436 |

In this section, the lateral and rotational rigidities of braces are expressed as the ratio of rigidities of braces to minimum required rigidities, \( K_u/K_{u0} \) and \( K_\beta/K_{\beta0} \). For continuously eccentric bracing, the value of the bracing rigidity from \( n=1 \) to \( n=2 \) is defined as the required rigidity. The coordinates \( K_u/K_{u0} \) and \( K_\beta/K_{\beta0} \) at the required rigidity are expressed as \( K_0 \). For numerical analyses, four points on the curve of \( K_0 \) in Fig. 7 are selected, and these coordinates are expressed as \( K_{M1}, 2.5K_B, 5K_U \) and \( 10K_U \). When a distance from \( (K_u/K_{u0}, K_\beta/K_{\beta0})=(1,1) \) to the curve of \( K_0 \) is shortest, the coordinates \( K_u/K_{u0} \) and \( K_\beta/K_{\beta0} \) on the curve of \( K_0 \) are defined as \( K_{M1} \). The value of \( K_u/K_{u0} \) on the curve of \( K_0 \) is fixed at 2.5, and then the value of \( K_u/K_{u0} \) depends on cross-sectional shapes and slenderness ratio. For \( 5K_U \) and \( 10K_U \), the value of \( K_u/K_{u0} \) on the curve of \( K_0 \) is fixed at 5.0 and 10, and then the value of \( K_\beta/K_{\beta0} \) depends on cross-sectional shapes and slenderness ratio. Non-structural members in the real truss structures have less than the required rigidity, so that 0.25\( K_0 \) to 0.5\( K_0 \) of bracing rigidities are selected as the analytical parameters in Appendix. For example, the coordinates on the curve of 0.5\( K_0 \) are half of the coordinate on the curve of \( K_0 \), thus the values of \( K_u/K_{u0} \) and \( K_\beta/K_{\beta0} \) for 0.5\( K_0 \) are half of these for \( K_0 \), respectively.
Fig. 7: Lateral and rotational rigidity of continuously eccentric braces.

Fig. 8 shows the elasto-plastic buckling behavior for H-shaped compression members with different type of braces. Figs. 8 (a)–(d) represent the relationship between the compression load, \( P/P_y \), the lateral displacement, \( u/l \), the torsional angle, \( \beta \), the rotational angle of each flange due to the web distortions, \( \alpha_1 \) and \( \alpha_2 \), and the axial displacement, \( \delta/\delta_s \), respectively. Then the plots \( \triangledown \), \( \triangledown \) in Fig. 8 (a) are the points at the maximum load, \( P_m \), and \( \triangledown \), \( \triangledown \) in Fig. 8 (a) are the yielding points. Where the maximum load, \( P_m \), is defined as the elasto-plastic buckling load. \( u \), \( \beta \), \( \alpha_1 \) and \( \alpha_2 \) in Figs. 8 (b)–(d) are the displacement at the center of members. The elasto-plastic buckling load, \( P_m \), for Type A with \( 2.5K_B \) is almost equal to that for Type B. On the other hand, the elasto-plastic buckling load, \( P_m \), for Type B with \( 10K_U \) is much larger than that for Type A with \( 10K_U \). The torsional angle, \( \beta \), at \( P_m \) for Type B with \( 10K_U \) is larger than that for Type A.

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Figure 8: Elasto-plastic buckling behavior for H-shaped compression members with eccentric braces.
After yielding, the torsional angle, $\beta$, for Type B increase rapidly. After yielding for H-shaped compression members, the reduction in the torsional rigidity for members is small, even though the torsional angle is larger. Then the members keep their strength after the members are inelastically buckled.

Fig. 9 shows the relationship between the lateral displacement, $u_1$, and the torsional displacement, $u_2-u_1$, at $P_m$ for different type of bracing rigidity.

![Figure 9: Relationship between lateral displacement and torsional displacement.](image)

Figure 9: Relationship between lateral displacement and torsional displacement.

$u_1$ is the lateral displacement of upper flange, and $u_2-u_1$ is the difference of lateral deformation between upper and lower flanges at $P_m$. Then for fig. 9, $u_1$ and $u_2-u_1$ is defined as lateral displacement and torsional displacement. For $K_M$ and $2.5K_B$, the lateral displacement, $u_1$, is much larger than the torsional displacement, $u_2-u_1$, and for $10K_U$ and $5K_U$, $u_2-u_1$ is much larger than $u_1$. When the lateral displacement is larger than the torsional displacement, the buckling mode of H-shaped members is called as the predominantly lateral buckling mode. Similarly, when the torsional displacement is larger than the lateral displacement, the buckling mode of H-shaped members is called as the predominantly lateral buckling mode. Therefore, the buckling mode for $K_M$, $2.5K_B$ is predominantly lateral buckling mode and The buckling mode for $10K_U$, $5K_U$ is predominantly torsional buckling mode. The relationship between the predominantly buckling deformation and the buckling stress must be investigated.

### 2.2 Elasto-plastic buckling behavior for H-shaped compression members with different eccentric bracings

Fig. 10 show the relationship $P_m$ for Type A and that for Type B. Fig. 10(a) compares the buckling load for the for Type A with or without the vertical stiffener, and Fig. 10(b) show the buckling load for the different type of braces. For Type A, the elasto-plastic buckling load, $P_m$, with the vertical stiffener is larger than that without the vertical stiffener, because the web distortion is restrained by the vertical stiffener. For predominantly lateral buckling mode, the elasto-plastic buckling load, $P_m$ for Type A is almost equal to that for Type B.
On the other hand, for predominantly lateral buckling mode, the elasto-plastic buckling load, $P_m$ for Type B with $10K_U$ and $5K_U$ is higher than that for Type A, because the torsional rigidity for Type A is higher than that of Type B due to continuously eccentric bracing.

Fig. 10: Relationship elasto-plastic buckling load.

Fig. 11 shows the relationship between lateral rigidity ratio $B_Ku/B_Ku0$, and the modified ratio, $\frac{B_Ku}{B_Ku0}$ for Type B. The plots represent the numerical analyses results for three kinds of the cross section. H-shaped members for Type B possess the only elasto-plastic buckling load for Type A with $B_Ku/B_Ku0 = 1$, even though $B_Ku/B_Ku0$ for Type B increases. The curve closed from solution of Eq. (21) is represented as the following in reference to the numerical analyses results.

$$
\frac{B_Ku}{B_Ku0} = 1 - 0.3\sqrt{\frac{B_Ku0}{B_Ku}}
$$

(21)

Fig. 11: Evaluation of equivalent bracing rigidity.
Then the elasto-plastic buckling load for Type A and Type B can be evaluated using the equivalent rigidity of eq. (21).

3 Conclusion

1) When the buckling mode of H-shaped members is the predominantly torsional buckling mode, the elasto-plastic buckling load for Type B is higher than that for Type A.
2) When the buckling mode is the predominantly torsional buckling mode, the equivalent bracing rigidity for the elasto-plastic buckling load of type A equal to that for Type B is obtained from Eq. (21).
3) When the buckling mode is the predominantly torsional buckling mode, the equivalent bracing rigidity for the elasto-plastic buckling load of type A equal to that for Type B is obtained from Eq. (21).

Appendix

Fig. A1 shows the coordinates of bracing rigidity of non-structural members for the real truss structure. Symbols show the case of non-structural members with channel section and angle section. The black solid curve represents the case of required bracing rigidity. According to Fig. A1, part of the non-structural member does not possess the required bracing rigidity.

![Figure A1: Bracing rigidity of non-structural members for real truss structures.](image)

References
