석고보드와 결합된 강재 샛기둥 패널의 부분 합성거동

Partial Composite Action of Gypsum-Sheathed Cold-Formed Steel Wall Stud Panels

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요 약 : 본 연구에서는 벽 패널의 부분 합성거동 해석에 대하여 거론한다. 기 발표된 목재 바닥 시스템으로부터 유도된 처짐공식을 소개하고, 이 공식을 적용하여 석고보드와 강재 샛기둥으로 결합된 합성벽 패널의 중앙지점 처짐값을 산정한다. 나사연결부의 불완전성(미끄럼), 국부좌굴, 샛기둥 복부의 개구부, 그리고 인접 석고보드간의 불연속으로 야기될 수 있는 강성의 감소 등을 처짐공식에 적절히 반영하는데 그 목적을 두었다. 적용된 처짐공식으로 산정된 처짐 기대치와 실험 관측치간의 비교에서는, 나사연결부의 상한 강성치를 사용한 처짐 기대치가 실험 관측치와 가장 근접한 결과를 보였다.

ABSTRACT : The problem addressed in this study is how to analytically treat the partial composite action for wall panels. An equation, derived for wood-joist floor systems, which determines deflections for beams with partial composite action is introduced. The equation is applied to the calculation of the mid-span deflection for gypsum-sheathed, cold-formed steel wall stud panels. The objective of this study is to properly reflect the influence of the following factors in the calculation of mid-span deflection for the panel: connection slip, local buckling, perforations in the stud web, and effects from joints in the sheathing. Predicted deflections based on an upper bound for connection rigidity were closest to experimental deflections.

핵 심 용 어 : 합성벽 패널, 냉간성형강재, 부분 합성거동, 국부좌굴, 벽체 샛기둥

KEYWORDS : composite wall panel, cold-formed steel, partial composite action, local buckling, wall stud

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1. INTRODUCTION

The focus of this study is a cold-formed steel wall stud panel sheathed by gypsum board as described in Fig. 1. The panel is treated as a simply supported beam set vertically with uniform lateral loading over its entire span, because it is assumed to be an interior, nonload-bearing wall panel. Cold-formed steel, lipped-channel flexural members, when loaded in the plane of the web of the stud, may buckle laterally if adequate bracing is not provided. But, because the gypsum board attached to both flanges of the stud by fasteners provides adequate restraint, the panels in this study are not subject to lateral-torsional buckling.

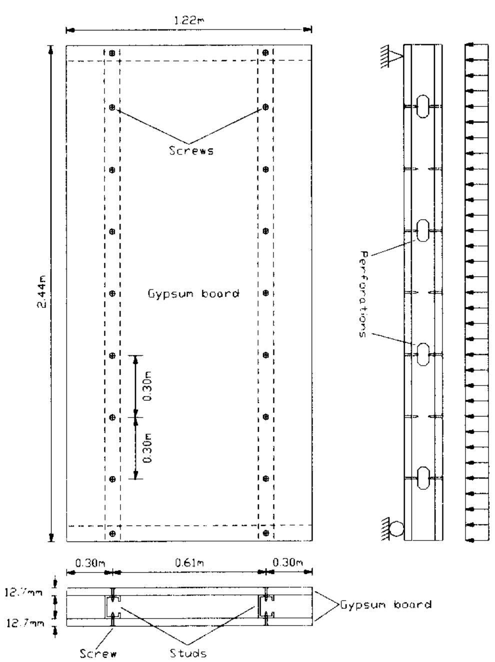

Fig. 1 Physical model (2.44m nominal span-panel)

The stiffness of a composite panel connected by fasteners is intermediate between that of a panel with rigidly connected components and that of a panel with completely unconnected components because of the slip at the screws between components. A deflection equation which considers the stiffness reduction due to the slip was developed by McCutcheon[1] for a simple floor system consisting of wood joists and subfloor as shown in Fig. 2.

The objective of this study is to determine the theoretical deflection of a cold-formed steel wall stud panel with gypsum board sheathing under lateral, uniformly distributed loading using a modified form of McCutcheons equation.

There are three primary factors (in addition to connection slip) reducing the stiffness of the composite panel: 1) local buckling behavior due to compressive stresses, from bending due to lateral loading, 2) perforations placed in the stud web for the purpose of simplifying placement of bracing and passage of utilities, and 3) effects of the joints over the length of the stud where

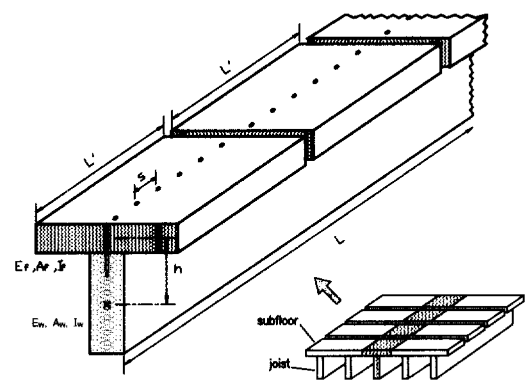

Fig. 2 T-beam model with subfloor and joist

the edges of the wallboard meet. Therefore, the main objective of this part is to properly reflect the influence of these factors in the calculation of deflections for composite panels. The method could then be used in design to determine limiting heights for wall panels including these effects. To check the method for calculating theoretical deflections, comparisons were made with experimental deflections from composite wall tests (Lee and Miller[2]) which were used to develop experimentally-based limiting heights.

2. LITERATURE REVIEW

2.1 Wood-Joist Floor Systems with Partial Composite Action

A study by McCutcheon[1] involves wood-joist floor systems connected by nails. In the analysis and design of wood-joist floor systems, it is often assumed that the system consists of joists which act as simple beams and a floor/subfloor which spans perpendicularly over the joists. McCutcheon expressed the deflection equation for simple beams with partial composite action under three different load cases (mid-span and quarter-point concentrated loads and uniformly distributed load) as follows:

$$\Delta=\Delta_R\left[1+f_\Delta\left(\frac{(EI_x)_R}{(EI_x)_U}-1\right)\right] \qquad (1)$$

where, Δ_R= deflection if the components of the beam are rigidly connected, f_Δ = a constant involving hyperbolic trigonometric functions of L, L = span length, $(EI_x)_R$ = stiffness if the components are rigidly connected, $(EI_x)_U$ = stiffness if the components are completely unconnected. In this equation,

$$\alpha^2=\frac{\bar{h}^2\cdot S_{slip}}{(EI_x)_R-(EI_x)_U}\left(\frac{(EI_x)_R}{(EI_x)_U}\right) \qquad (2)$$

where $\bar{h}$= distance between centroids of principal moment-carrying members, S_{slip} = shear load per unit span length which causes a unit slip in the nail or adhesive joint between principal moment-carrying members. Note that wallboard fastener connection test method for S_{slip} is described by the author (Lee[3])

The bending stiffness value $(EI_x)_R$ can be computed for a rigidly connected T-beam model for a subfloor and joist system by the transformed area method as follows:

$$(EI_x)_R=(EI_x)_U+\frac{(EA)_f\cdot(EA)_w}{(EA)_f+(EA)_w}h^2 \qquad (3)$$

where $(EA)_f$ and $(EA)_w$ = axial stiffnesses of the flange and web, respectively. Note that $\bar{h}$ in Eq. (2) is h for the wood floor system (T-beam) and $2h$ for a lipped channel section stud panel (I-beam) where h = distance between centroids of the stud gross section and each side of wallboard.

Noting that $\Delta/\Delta_R=(EI_x)_R/EI$, the stiffness of the composite beam, EI, is computed directly as follows:hat

$$EI = \frac{(EI_x)_R}{1+f_\Delta\left(\frac{(EI_x)_R}{(EI_x)_U}-1\right)} \tag{4}$$

As a simple method for computing f_Δ, McCutcheon[1] suggested the following approximate equation for all three load cases (mid-span and quarter-point concentrated loads and uniformly distributed load):

$$f_\Delta = \frac{10}{(L\alpha)^2+10} \tag{5}$$

and verified that the exact and approximate values for all three load cases are in close agreement.

Until now, the analysis of the composite action for wood-joist floor systems has not considered the effects of joints in the subfloor. The sheets that make up the subfloor are perpendicular to the joists, and there are many joints over the length of the joist where the edges of the subfloor sheets meet. McCutcheon[1] suggested a method for treating the effects of joints in his study. The problem of the joints can be addressed using the factor L' instead of L in Eq. (5) as:

$$f_\Delta = \frac{10}{(L'\alpha)^2+10} \tag{6}$$

where L' = distance between the joints in the sheathing.

3. ANALYSIS

3.1 General

The model used in this study was adapted from a study by William J. McCutcheon who modeled a wood-joist floor system as a series of T-beams. McCutcheon[1] derived a mid-span deflection equation for the system (see Eq.(1)), and this equation was adapted to calculate the deflection of the steel stud panel in the composite wall tests shown in Fig. 1. To account for the different geometry and material properties, the stiffness equation for rigidly connected components is changed from Eq.(3) to the following:

$$(EI_x)_R = E_s\left[I_{avg} + \frac{2(I_{wb}+A_{wb}\cdot h^2)}{n}\right] \tag{7}$$

where E_s = steel modulus of elasticity, I_{avg} = average moment of inertia for effective sections considering both unperforated and perforated portions, I_{wb} = moment of inertia for the wallboard (one side), A_{wb} = cross sectional area for the wallboard (one side), h = distance between centroids of the stud gross section and each side of wallboard, n = modular ratio = E_s / E_{wb}, and E_{wb} = modulus of elasticity of wallboard. Finally, the stiffness for completely unconnected components is calculated as follows:

$$(EI_x)_U = E_s\cdot I_{avg} + 2(E_{wb}\cdot I_{wb}) \tag{8}$$

Note that the composite panel consists of two cold-formed steel studs sheathed on both sides with gypsum board, as shown in Fig. 1.

To determine S_{slip}, a series of wallboard fastener connection tests was performed by author[3]. The objective of this test series was to determine S_{slip} (shear load per unit length that causes a unit slip in the fastener joint). For deflection predictions to compare with the experimental deflections, a potential range in S_{slip} from 214 to 1724 (kPa) was determined for 12.7 (mm) thickness of gypsum board with #6 bugle head screws and 305 (mm) fastener spacing.

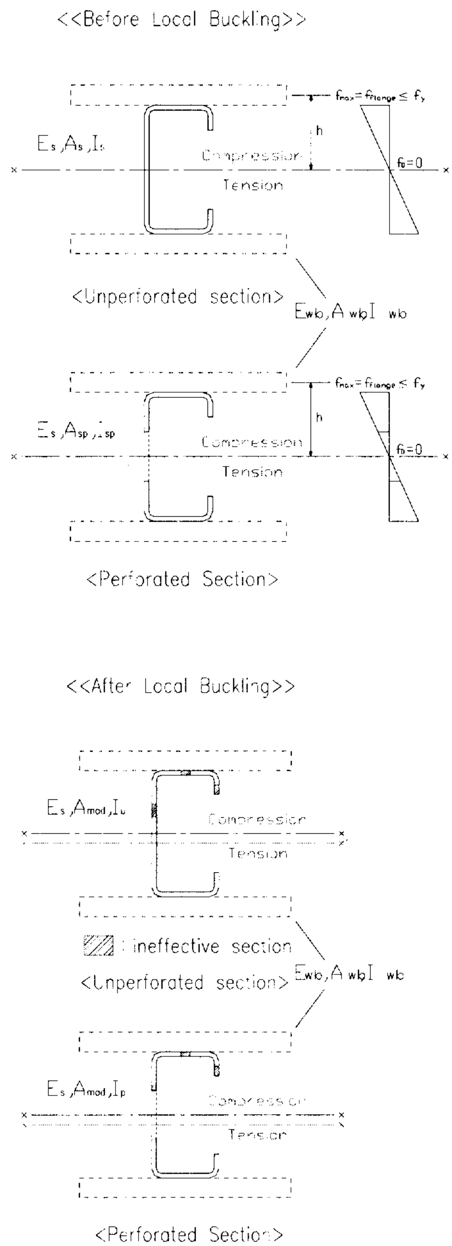

Fig. 3 Effective sections for bending

3.2 Local Buckling for Unperforated and Perforated Sections

The steel studs examined in this study have several perforations in the web to simplify passage of utilities. Local buckling effects for both unperforated and perforated sections are idealized as shown in Fig. 3. The panel is treated as a beam subjected only to bending resulting from the uniformly distributed applied lateral loads. The maximum compressive stress in the stud derived from the maximum bending moment (at mid-span) occurs at the top of the flange ($f_{max}= f_{flange}$). And, because the studs are symmetric, the neutral axis (x-axis) lies along the center of the web (f_0 = 0) when the section (gross section) is fully effective. It is assumed that the compression stress varies linearly from zero at the center of the web to f_{max} at the top of the flange, and that the maximum tensile stress is equal to the maximum compressive stress. If local buckling behavior occurs, it will decrease the bending stiffness of the steel stud and shift the neutral axis to x. The compressive portions of the flange, web, and lip must all be checked for local buckling. For the tensile portions, no local buckling occurs, and that portion of the section is fully effective. The effective section is used to approximate the stiffness remaining in a stud after local buckling occurs. As local buckling effects increase, the effective section properties decrease.

The calculations for effective section properties are guided by the AISI specification[4]. However, this specification provides no guidance for sections with rectangular perforations. The web elements in the perforated section are treated as unstiffened strips in the calculation of net effective section (Miller[5]). The effect of stiffness loss due to local buckling behavior and the effect of perforations are both reflected in a weighted average of the moments of inertia for the unperforated and perforated sections as follows:

$$I_{avg} = \frac{I_u L_u + I_p L_p}{L_u + L_p} \tag{9}$$

where I_u and I_p represent moments of inertia for unperforated and perforated sections, respectively. and L_u and L_p represent the total lengths of unperforated and perforated sections between supports.

4. COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL DEFLECTIONS

The test series consisted of 49 tests of wall panels (see Fig. 1) with the following characteristics:

(1) sheathed on both sides with 12.7 *mm* gypsum board
(2) 1.22 *m* wide panels
(3) nominal 1.22 *m*, 2.44 *m*, 4.27 *m*, and 4.88 *m* height panels
(4) 41, 64, 89, 102, and 152 *mm* stud depths
(5) 31.8 *mm* flange width
(6) 0.51 *mm* (25 gauge) and 0.89 *mm* (20 gauge) stud thicknesses
(7) 367 *MPa* (25 gauge) and 313 *MPa* (20 gauge) yield stresses (F_y)
(8) 6.4 *mm* (for 25 gauge) and 9.5 *mm* (for 20 gauge) lip dimensions
(9) stud spacing at 0.61 *m*
(10) Wallboard attached with #6 screws (25.4 *mm* long) (regular screws for 25 gauge and self-drilling screws for 20 gauge) spaced at 0.30 *m* on center of each flange.

The predicted deflections determined as explained in the Analysis section were compared with the experimental deflections from the composite wall tests (Vertical tests) (Lee and Miller[2]). The overall results for predicted deflections for maximum (1724 *kPa*) and minimum values of S_{slip} (214 *kPa*) are plotted as shown in Figs. 4 and 5, respectively. Note that maximum and minimum values of S_{slip} indicate the largest and the smallest shear resistances between 0.2 and 0.8 times the failure load, and that, for comparison, these deflections are plotted as the ratio of experimental deflection to theoretical deflection versus the applied loads. From Figs. 4 and 5, it is notable that the deflections for maximum S_{slip} are closer to experimental deflections. The means and standard deviations for all two cases are as follows:

(1) $\bar{x}$ = 0.969, and S.D. = 0.133 for max. S_{slip},
(2) $\bar{x}$ = 0.781, and S.D. = 0.147 for min. S_{slip},

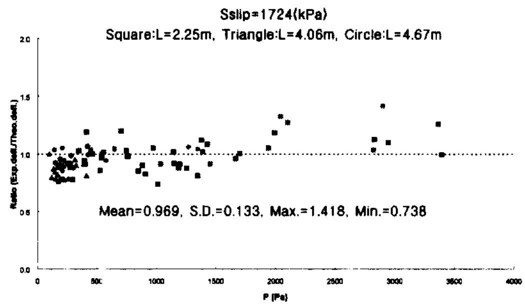

Fig. 4 Deflection comparison for max. S_{slip}

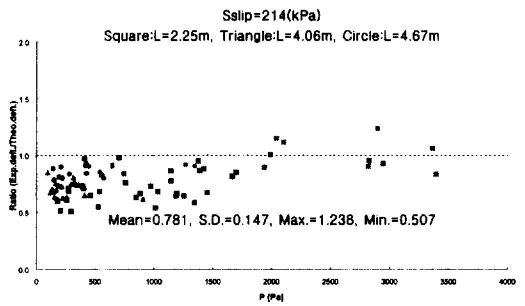

Fig. 5 Deflection comparison for min. S_{slip}

As shown in both figures, it is found that as the loading increases, the ratios increase with a similar distribution. The slight increase in the ratio with increased loading is probably a reflection of the gradual softening of the actual wall panel system, not accounted for in the use of constant values of S_{slip} and gypsum board modulus in the calculated deflections.

5. CONCLUSIONS

5.1 General

From Figs. 4 and 5, it was found that as the loading increased, the ratios (experimental deflection/predicted deflection) increased slightly as expected due to the gradual softening of the panel system. Comparing Fig. 4 with Fig. 5, it is notable that the deflections for maximum S_{slip} are closer to the experimental deflections. The differences between the predicted and experimental deflections may come from the highly variable nature of the wall panel system (especially connection stiffness, because of the effects of fastener misalignment and potential local damage to the wallboard).

5.2 Recommendations for Future Work

The following efforts are recommended for further study:

(1) The results from the wallboard fastener connection tests for S_{slip} used in the deflection predictions are very conservative bounds. Therefore, one needs to determine more reasonable results from the tests to use in design. In addition, an alternate approach for determining S_{slip} values could be investigated by back-calculating to match theoretical and experimental deflections.

(2) A constant value of S_{slip} was used for all connections in a panel. An improved deflection calculation may be obtained by accounting for the variation in connection stiffness along the length of the panel (due to nonlinear stiffness of the connection), and for changes in stiffness with increased load/deflection.

(3) Only panels sheathed with 12.7 *mm* thick gypsum board were considered

in this study. Different thicknesses of gypsum board and other sheathing materials should also be investigated.

(4) The AISI specification provides two procedures for determining effective widths for deflection determination. Procedure 1 was used in this study. An analysis using Procedure 2 should also be considered.

(5) The additional stiffness due to the galvanized coating for the steel stud was ignored in the stiffness calculation. Because the thickness of the stud strongly affects the determination of the deflection, consideration of the additional stiffness should be evaluated.

(6) The use of the unstiffened strip method for determining effective widths for perforated webs was developed for strength calculations. Its use here for deflection determinations needs additional study.

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