냉간성형강재 벽체 패널의 한계높이 산정

Limiting Height Evaluation for Cold-Formed Steel Wall Panels

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요 약 : 본 연구의 목적은 석고보드로 둘러 싸여진 냉간성형강재 벽체패널의 실험에 근거한 한계높이를 산정하는 것이다. 이 패널은 내장 비내력벽으로서 등분포하중이 측면으로 작용된다고 가정한다. 한계높이는 처짐공식 뿐만 아니라 휨, 전단, 그리고 복부판 압착을 고려한 강도에도 기초하여 산정된다. 3가지 처짐제한(L/360, L/240, L/120)에 대한 한계높이는 전형적인 설계압력 범위에 걸쳐 산정된다(여기서 L은 벽체의 높이임).

ABSTRACT : This study aimed to develop experiment-based limiting heights for interior, nonload-bearing, cold-formed steel wall panels sheathed with gypsum board and subjected to uniformly distributed lateral loadings. The limiting heights were evaluated by their strength (for flexure, shear, and web crippling) and deflection. Limiting heights for deflection limits of L/360, L/240, and L/120 (where L is the height of the wall) were developed over the range of typical design pressures.

핵 심 용 어 : 냉간성형강재, 합성벽 패널, 벽체 샛기둥, 비내력벽, 한계높이
KEYWORDS : Cold-formed steel, composite wall panel, wall stud, non-load-bearing wall, limiting height

1. INTRODUCTION

Interior walls and permanent or temporary partitions must be designed to resist loadings, such as those form earthquake, wind, and other building occupancy-related forces, applied perpendicular to the plane of the walls. The 1997 *Uniform Building Code*(UBC) [International Conference of Building Officials(ICBO) 1997(4), Section 1611.5] requires that interior walls and partitions "that exceed 1,830 mm(6 ft) in height shall be designed to resist all loads to which they are subjected but not less than a load *L* of 240 Pa(5 psf) applied perpendicular to the walls. The 240 Pa load need not be applied simultaneously with wind or seismic loads. The deflection of such walls under a load of 240 Pa shall not exceed 1/240 of the span for walls with brittle finishes and 1/120 of the span for walls with flexible finishes." Seismic design requirements must also be considered in general where they are more restrictive.

2. PURPOSE OF THE STUDY

The purpose of this study is to develop experimentally based limiting heights for interior, non-load-bearing, cold-formed steel wall panels sheathed with gypsum board and subject to uniformly distributed lateral loadings. The limiting heights generated for ASTM C 754-98a(3) allow designers to meet the UBC(4) requirements described above, as well as more restrictive loading

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and deflection requirements if appropriate to a particular application. Testing complied with ICBO Evaluation Service(ES) AC86[6] and ASTM E 72-82[1] using a uniform, vacuum chamber loading on vertical, 1.22m(4 ft) wide specimens. Limiting heights for deflection limits of $L/360$, $L/240$, and $L/120$(where L is the height of the wall) are developed over the range of typical design pressures.

3. VERTICAL TEST SPECIMENS

Cold-formed steel wall studs were spaced at 610 mm(24 in.) on center, sheated on both sides with 12.7mm(1/2 in.) gypsum board as shown in Fig. 1, and tested in a vertical orientation, simulating service conditions. The test series(Lee and Miller[8]) consisted of 49 tests of wall panels with the following characteristics:

1) Width of 1.22m(4 ft)
2) Sheathed on both sides with 12.7mm(1/2 in.) gypsum board
3) Nominal 1.22m(4 ft) and 2.44m(8 ft) height panels sheathed with one sheet on each side (no joint), nominal 4.27m(14 ft) height panels sheathed with one 3.66 m sheet and one 0.53 m sheet on each side, with the joints staggered(Fig. 1), nominal 4.88m(16 ft) height panels sheathed with one 3.66 m sheet and one 1.14m sheet on each side, with the joints staggered
4) Gypsum wallboard attached with #6 screws [25.4mm(1 in.) long](regular screws for 0.455 mm thick studs and self-drilling screws for 0.836 mm thick studs) spaced at 305mm(12 in.) on center of each flange
5) Nominal 0.836mm(0.0329 in.) and 0.455mm (0.0179 in.) minimum base metal thicknesses for the steel studs with nominal minimum yield stress of 228 MPa(33 ksi)
6) Stud depths of 41.3 mm (1.625 in.), 63.5mm (2.5 in.), 88.9mm(3.5 in.), 101.6mm(4 in.), and 152.4mm (6 in.)
7) Flange width of 32mm(1.25 in.)
8) Stiffening lips of 3.2mm(for 0.455mm thickness) and 9.5mm(for 0.836mm thickness)
9) Minimum specified yield stress, F_y=227.4 MPa

During the fabrication of the test specimens, the gypsum board was randomly selected from that supplied by three different manufacturers. Each wall panel specimen was fabricated using gypsum board from two different manufacturers on the two opposite faces of the panel. The Gypsum Association sponsored tests[7] to determine the flexural strength of several types of commonly used 12.7mm(1/2 in.) gypsum board products(regular gypsum board, moisture-resistant board, Type X, and veneer base). The Gypsum Association used these flexural strength test to indicate which type of gypsum board may provide the least increases to stiffness and strength of the composite system and thus provide conservative composite wall test results for the other types. The regular gypsum board yielded the lowest flexural strength and was used for the composite wall testing, based on the recommendation of the Gypsum Association, to provide limiting heights applicable to all of the 12.7 mm(1/2 in.) products listed above.

In addition, two nominal 2.44m(8 ft) height tests were conducted using Type X gypsum board and 0.455mm nominal base metal thickness, 88.9mm deep studs. In comparing these tests with similar nominal 2.44m height tests using regular gypsum sheathing, it was observed that the Type X board provide slightly greater composite bending stiffness and flexural strength. This provides additional confirmation for the conservative use of the regular gypsum board in the test series.

The steel studs tested conformed to ICBO ES AC46[5] as required by ICBO ES AC86[6]. Mill reports for the studs were provided describing the steel yield stress, tensile strength, chemical composition, thickness, and percent elongation. Yield stress and tensile strength were also evaluated independently (per ASTM A370-91a[2]) by testing three tensile coupons from each slit coil of used in the fabrication of the studs. Small samples of steel were also cut after testing from the web of each stud, and three thicknesses were measured (and averaged) for each of these specimens, both before and after removing the galvanized coating. Thirty-eight percent reagent grade HCl was used to remove the zinc coating. Base metal thickness measurement were used for stud dimensions and properties.

Overall width of each specimen was 1.22m. In general, set of two similar specimens were tested at nominal heights of 1.22 and 2.44m and at taller heights(4.27 and 4.88m) for each different combination of stud depth and thickness listed previously. The 1.22m tests were conducted for the nominal 0.455mm base metal thickness studs to (1) determine experimentally both the shear capacity and the strength in a web crippling failure mode; and (2) evaluate experimentally a potential horizontal shear failure along the screw connections between the studs and sheathing in a high shear condition.

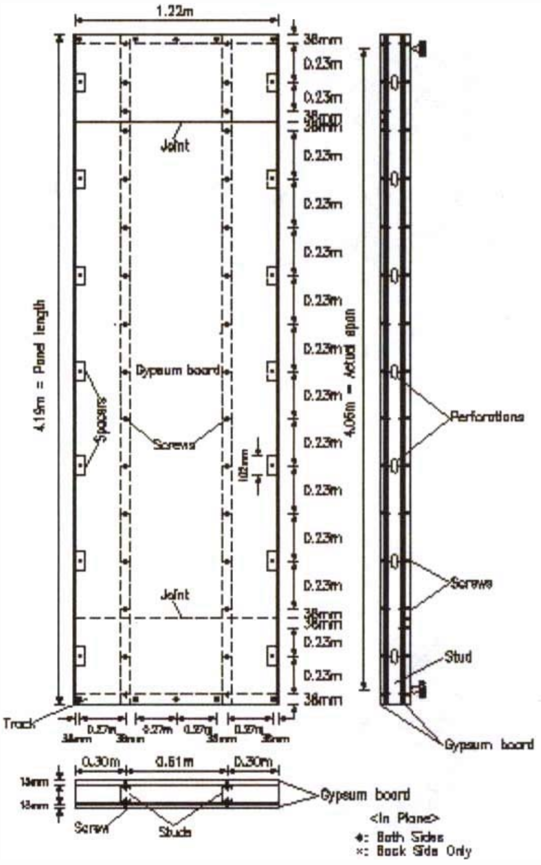

Fig. 1 Test specimen (4.27 m nominal span panel)

4. TEST APPARATUS

The chamber method of loading was used with an airtight frame surrounding the specimen. A polyethylene sheet covered the specimen, overlapped the frame, and was sealed to resist air leakage as shown in Fig. 2. A vacuum pump was used to reduce air pressure between the specimen and the wall of the chamber. The difference between the chamber and ambient air pressure was measured with both a digital(0-330mm H_2O range) and a U-tube manometer.

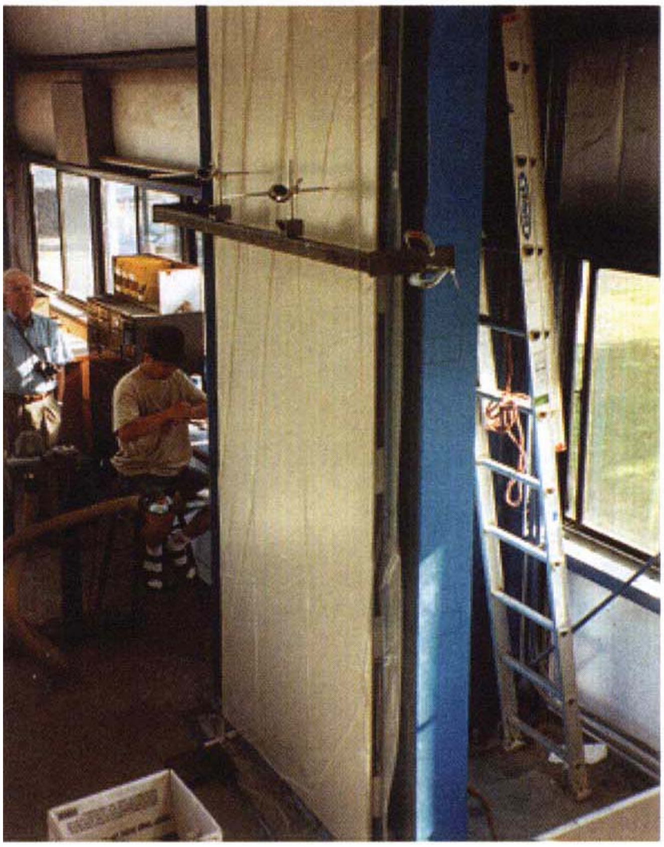

Fig. 2 Test apparatus for nominal 4.88 m panel

Cylindrical roller supports [on the negative pressure(back) side of the panel] were placed near the top and bottom of the specimen to reduce rotational restraint. For all but the nominal 1.22m height tests, the wall specimen's lower track also rested on a roller support. For the nominal 1.22 m height tests, the lower track was screwed directly into a 25mm thick wooden base that was bolted to the bottom of the test frame. This better simulated the actual bottom end support condition for these tests to examine the effects of high shear forces. Restraints at the top end of the panel to hold the vertical assembly safely in place during testing were designed to minimize additional rotational restraint (see Fig. 3).

Midheight lateral deflections were measured using two mechanical dial gauges, aligned with each of the steel studs in the wall assembly, and mounted on a stiff reference frame. The average of the deflection readings from the two gauges was used to determine the midheight deflection of the test assembly at each loading increment. A deflection reading was also made at the bottom of the wall to monitor movements at the base. A photograph of the test set-up is shown in Fig. 2

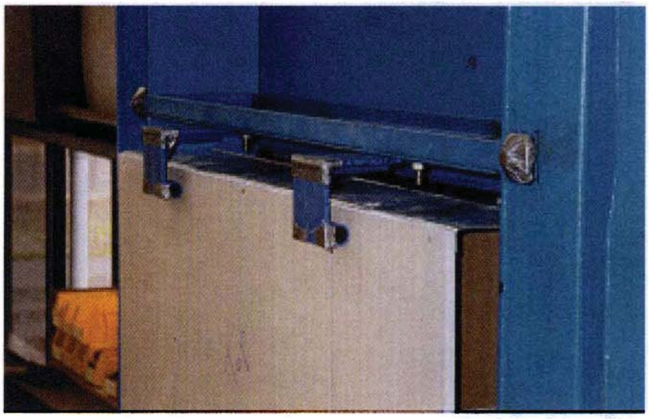

Fig. 3 Out-of-plane motion restraint at top of the panel

5. TESTING PROCEDURE

The testing procedure was prescribed in ICBO ES AC86[(6)] and ASTM E 72-80[(1)]. The loading was applied at a rate not exceeding 140 Pa (3 psf) per minute. Successive incremental loadings were applied for 5minutes to achieve a deflection of *L*/360(to fully seat the assembly in the test fixture) and then to the specified deflection limits of *L*/360 (again), *L*/240, and *L*/120. For each of these four increments, deflections were measured on initial application of each load increment, after 5minutes of set, after release of the load increment, and again after 5minutes of set.

After incremental loadings to the specified deflection limits, if the specimens had not already failed, the specimens were loaded to failure to provide data on controlling failure modes and ultimate loads for the wall panels and the capacity of the connections between the gypsum board and the steel studs in developing composite action. Failure was defined as when the maximum pressure could not be sustained without sudden or continuous movement of the test specimen. Typical failure modes(flexural failure, web crippling, and collapse of wallboard) observed in the tests are shown in Fig. 4, 5 and 6, respectively.

Fig. 4 Flexural failure

Fig. 5 Web crippling

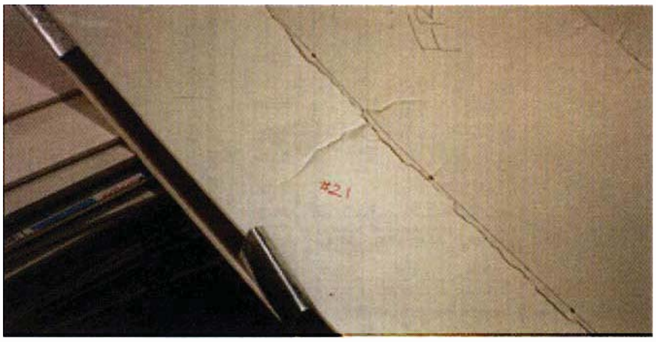

Fig. 6 Collapse of wallboard

6. LIMITING HEIGHTS BASED ON DEFLECTION

Conservative limiting heights based on deflection were determined from a thorough analysis of the vertical composite wall test results. An average composite bending stiffness *EI* was determined from the test results for each wall panel specimen, averaging the composite bending stiffness *EI* values determined from deflection measurements from each of the two dial gauge aligned with each of the studs, as well as averaging the composite bending stiffness *EI* values for each of the load increments (*L*/360, *L*/240, and *L*/120) applicable for each tested wall panel for each tested height. Then, to produce the overall limiting height tables, as shown in Table 1, and 2, from the test series, composite bending stiffness *EI* values for similar(height and stud thickness/depth) tests were also averaged to determine the limiting height based on deflection.

Composite bending stiffness *EI* includes the effects of both the gypsum board and the steel studs and was based on the equation for the midspan deflection of a simply supported beam with a uniformly distributed loading over its entire span

$$EI = \frac{5wL^4}{384\Delta} \qquad (1)$$

where *EI*=composite bending stiffness; *w*= load/unit length of the panel (measured pressure for set deflection after application of load multiplied by 1.22 m panel width); *L*=actual vertical span between supports; and Δ=incremental deflection measured from previous set deflection after release of previous load to current set deflection after application of the current load.

Composite (*EI*) for each load increment was calculated based on the incremental deflection from the previous set deflection after release of the previous load to the new set deflection after application of the new, higher load. In the testing here, the composite bending stiffness *EI* was observed to generally(but not always) increase with test panel height. In addition, the stiffness was also seen to generally(but not always) decrease with increased deflection and loading, showing a softening type of behavior.

For nominal 2.44-4.88m height panel tests generating projected limited height greater than 4.88m, a linear extrapolation(permitted per ICBO ES AC86$^{(6)}$) of the resulting average composite stiffness *EI* values was performed. Limiting heights derived from the panel tests were limited to no greater than twice the panel height per ICBO ES AC86$^{(6)}$.

Table 1. Limiting heights(m) for 0.455mm thick steel studs

Stud depth	Deflection limit	Lateral loading			
		240 Pa	360 Pa	480 Pa	720 Pa
41.3mm	L/360	N/A	N/A	N/A	N/A
	L/240	2.41	N/A	N/A	N/A
	L/120	2.97	2.44	N/A	N/A
63.5mm	L/360	2.82	2.46	N/A	N/A
	L/240	3.23	2.82	2.57	N/A
	L/120	3.61	2.95	2.57	N/A
88.9mm	L/360	3.53	3.07	2.77	2.31
	L/240	4.09	3.35	2.87	2.31
	L/120	4.19	3.35	2.87	2.31
101.6mm	L/360	3.76	3.28	2.97	2.57
	L/240	4.32	3.68	3.18	2.57
	L/120	4.60	3.68	3.18	2.57
152.4mm	L/360	5.11	4.09	3.48	2.72
	L/240	5.11	4.09	3.48	2.72
	L/120	5.11	4.09	3.48	2.72

N/A: data not available

7. LIMITING HEIGHTS BASED ON STRENGTH

Allowable heights of the steel wall studs alone based on flexure, shear, and web crippling failures, including the effects of local buckling, were calculated for each test in accordance with ICBO ES AC46$^{(5)}$. The beneficial contribution of the gypsum board is neglected in these calculations (because the gypsum modulus of elasticity (E_{wb}= 1550 MPa) is very small when compared to that of a steel (E_s=203,255 MPa)), except for the restraint provided against lateral buckling.

Table 2. Limiting heights(m) for 0.836mm thick steel studs

Stud depth	Deflection limit	Lateral loading			
		240 Pa	360 Pa	480 Pa	720 Pa
41.3mm	L/360	2.36	N/A	N/A	N/A
	L/240	2.72	2.36	N/A	N/A
	L/120	3.40	2.97	2.72	2.36
63.5mm	L/360	3.10	2.67	2.39	N/A
	L/240	3.58	3.10	2.77	2.39
	L/120	4.60	4.01	3.58	3.10
88.9mm	L/360	4.01	3.51	3.18	2.77
	L/240	4.62	4.01	3.63	3.18
	L/120	5.82	5.08	4.62	4.01
101.6mm	L/360	4.39	3.78	3.43	2.95
	L/240	5.05	4.39	3.96	3.43
	L/120	6.38	5.56	5.05	4.39
152.4mm	L/360	5.79	5.08	4.60	3.89
	L/240	6.63	5.79	5.26	3.89
	L/120	8.36	7.32	5.82	3.89

N/A: data not available

The test results from the nominal 2.44m height and taller wall tests were used to demonstrate that the proposed connection between the gypsum sheathing and the steel studs develops composite action. The nominal 1.22m height tests were used in this series to investigate a higher shear condition. The composite wall assemblies were capable of resisting at least 1.5times the load causing maximum deflection(the deflection limit being considered for the limiting height calculation, typically *L*/120, *L*/240, or *L*/360) as required by ICBO ES AC86(6). In cases where ICBO ES AC46(5) does not have provisions for the calculation of shear or web crippling strengths without web stiffeners, and in fact for all of the nominal 0.455mm bare metal thickness studs, the shear and web crippling strengths(without stiffeners, but including the beneficial effects of the track and gypsum board) were evaluated experimentally in a high shear/end reaction condition using the results from the appropriate nominal 1.22m height panel tests. The end reaction for a uniformly loaded simple span of *wL*/2 provides a conservative estimate of the shear/web crippling strength for the nominal 1.22 m height panels. These panels were simply supported at the top and had the lower track at attached by screws to a wooden plate at the base. All of the observed shear/web crippling failures were at the base, which attracted more load than the top because of the additional end restraint. Thus, using *wL*/2 as the strength is conservative (less than the actual reaction force at the base of the panel at failure). A factor of safety of 3.0 was used in this evaluation based on the recommendation of ICBO ES(6) (P. Bahlo, personal communication). Thus, the controlling theoretical limiting heights(per ICBO ES AC46(5)) considering the web crippling(ignoring the perforation) and shear failure (for perforated web) modes are listed. The web crippling failure mode controls over the shear failure mode in all cases here. The heights were calculated using the nominal properties and dimensions for the studs.

Allowable heights of composite wall systems based on the flexural strength of the studs acting compositely with the gypsum board were determined based on the tests of the panels to failure. Failure was defined as when the maximum pressure could not be sustained without sudden or continuous movement of the test specimen.

The limiting heights based on the ultimate loads from the flexural testing were derived using the following method prescribed by ICBO ES AC86(6) [with the exception of including a factor of 0.75 on *P* for all lateral loads, including 240 Pa(5 psf)], which assumes a constant section modulus:

$$L_b = \left(\frac{R L_t^2}{1.5P\left(f_{yact}/F_y\right)} \right)^{1/2} \qquad (2)$$

where Lb=limiting height based on flexure(m); R= ultimate test load (Pa); Lt=test span(m); P= design load (Pa) (allowable load shall be limited to 240, 360, 480, and 720 Pa); fyact=actual yield strength of steel (MPa); and Fy=specified yield strength of steel(228 MPa).

Linear interpolation between the multiple test heights was used and is permitted per ICBO ES AC86(6) to derive limiting heights based on flexural strength between the 2.44 m height and the taller panel height.

Recommended limiting heights thus reflect actual observed strengths and failure modes from the panel tests, using appropriate factors of safety. None of the test specimens had a permanent set greater than 25% of the total deflection, thus meeting the ICBO ES AC86⁽⁶⁾ requirement. Where limiting heights based on strength were less than those determined based on deflection from the tests, the lower heights based on strength controlled the limiting height value.

8. OVERALL LIMITING HEIGHTS

Limiting heights, based on both deflection and strength, for similar(height and stud depth/gauge) panels were averaged. For those studs generating the smallest limiting heights, the nominal 2.44m height test results were used directly for generating all limiting heights greater than the actual span in the tests. Limiting heights smaller than the actual span were not used. When both nominal 2.44m tests and taller tests were conducted, the limiting heights derived from the different height tests were linearly interpolated(with equal test span and limiting height) as follows:

$$L=\frac{(L1\cdot H2-H1\cdot L2)}{(H2-H1-L2+L1)} \tag{3}$$

where $L=H$=interpolated limiting height; $L1$= actual span for nominal 2.44 m test; $L2$=actual span for taller test; $H1$=limiting height from nominal 2.44 m test; and $H2$=limiting height from taller test. If the taller test specimens yielded limiting heights greater than the actual span from the taller height tests, then the limiting heights derived from these taller height tests were used.

Finally, maximum stud heights to be used in design were determined by taking the smallest from all of the strength and deflection-based limiting heights as controlling.

9. CONCLUSIONS

Summary tables for the controlling limiting heights based on strength and deflection are presented in Tables 1 and 2. The values are slightly different in a few cases from those published in ASTM C 754-98a⁽³⁾ and correct minor errors in the initial modification of that standard.

Design applications of these results should include consideration by the responsible professional engineer of the potential effects of humidity and moisture content, repeated loads, damage to studs and gypsum board, and improper installation. The tests were conducted as described in this paper, and the study of these effects was not within the scope of the effort.

The composite wall tests were performed on typical studs and gypsum board with the nominal dimensions and material properties described in this paper. All studs were spaced at 610mm(24 in.). The limiting height tables presented in this paper are considered to be appropriate for the design of walls with studs having the same nominal dimensions and material properties as those tested. Extrapolation of the test results to other substantially different walls, or to larger stud spacings, should be accomplished only by a licensed professional engineer with a good understanding of the test methods and calculation procedures used to generate the results from these tests. Maximum stud heights from ASTM C 754-98a⁽³⁾ are also applicable to walls with studs spaced closer than 610mm on-center as well as to walls sheathed with gypsum board greater than 12.7mm in thickness and to walls with multiple layers of gypsum board, as these walls will in general be stiffer and stronger than tested.

Finally, this study will be useful to a similar testing to determine the limiting heights for a broader range of steel stud types and to determine more accurately the limiting heights for walls with different stud spacings commonly used in construction.

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