Macro-Modelling Approach for the In-Plane Cyclic Response of Cold-Formed Steel Partition Walls

Dong-Hyeon Shin and Hyung-Joon Kim

Department of Architectural Engineering, University of Seoul, Seoul 20504, Korea; donghyeon_shin@uos.ac.kr
* Correspondence: hyungjoonkim@uos.ac.kr; Tel.: +82-02-6490-2763

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Abstract: Past earthquakes demonstrate that non-structural elements could be vulnerable to a relatively low intensity ground shaking which induces negligible structural damage. The study aims to improve previously developed macro-models of cold-formed steel (CFS) partition walls to properly capture their in-plane cyclic response and damage states of important components in a CFS partition wall under imposed excitation. An effective analytical modelling approach is adopted for a simple modelling procedure and less computational effort. The proposed analysis model of partition walls consisting of several lumped spring elements is verified using direct comparison with two full-scale CFS partition wall tests. The analytical and experimental results are compared in terms of force–displacement relations, dissipated energy, and an influential damage mechanism of components consisting of partition walls. The comparison shows that the analytical model well captures the experimental response such as the overall strength and stiffness degradation and pinching behavior. Moreover, the damage mechanism predicted by the analytical model is in good agreement with that observed during the tests.

Keywords: cold-formed steel partition walls; in-plane deformation; macro-modelling approach; quasi-static test; damage states

1. Introduction

It has been demonstrated during past earthquakes that non-structural elements could be vulnerable to a relatively low intensity ground shaking which induces negligible structural damage [1–3]. Reports on the investigation of earthquake-induced-loss, therefore, show that economic loss due to non-structural elements exceeds that due to structural members [4]. The loss of non-structural elements largely results from moderate or extensive damages to the cold-formed steel (CFS) partition walls that are potentially required to be repaired or completely replaced after an earthquake. A CFS partition wall usually consists of tracks, studs, gypsum boards, their joints and connections between tracks and structural members. Mitigation of seismic damage to CFS partition walls is recognized as an important approach to reduce potential economic burdens for a building. This implies that the seismic performance of CFS partition walls needs to be rigorously identified, and then evaluated through reliable analytical prediction of their cyclic response behavior.

Various research on the analytical modelling of CFS walls has been carried out [5–7]. Previous studies focused on the analytical modelling of structural shear walls consisting of CFS members. There is, however, limited research on modeling capturing the structural behavior of CFS partition walls used for a nonstructural component [8,9]. Of the limited number of available analytical models for CFS partition walls, Paevera [10] and Nithyadhanran and Kalyanaraman [11], respectively, proposed micro finite element modelling or lumped modelling approaches. Based on the experimental results identifying the cyclic response of individual partition walls [12,13], Restrepo and Lang [14], Davies et al. [15], and Wood and Huchinson [16] suggested analytical modellings which can define the hysteresis of
CFS partition walls using several deterministic parameters such as the initial stiffness, yield strength, post-yielding stiffness ratio, etc. These models also utilize coefficients for calibrating a peak-oriented hysteretic model to reflect their possible variations. Although the global cyclic behavior of a CFS partition wall represented by a single lumped element can be easily captured, it is hard to estimate its local behavior and damage mechanism. Rahmanishamsi et al. [17] suggested a more detailed analytical modelling, called a phenomenological model. This model was constructed using nonlinear and/or linear multi-spring elements which can represent the main components of CFS partition walls and their connections. Such a modeling approach has been considered a powerful one in terms of simulating the global nonlinear force–displacement relations of a CFS partition wall and its local damage sequence under seismic attack. Applications of the detailed model are questionable because of the time-consuming computations in time-history dynamic analyses and numerical complexities. Similar to the models with a single lumped element, deterministic parameters are still needed to construct the hysteresis rules that should be determined by component-level experimental results of components and connections of a CFS partition wall.

The previously developed macro-models for CFS partition walls should be improved to overcome the disadvantages mentioned above. In order to address this, a more effective analytical modelling approach needs to be developed to easily construct and simulate the monotonic and cyclic responses of CFS partition walls. This study aims to propose a macro-analytical model for capturing in-plane responses of CFS partition walls which can be constructed with a simple modelling procedure and less computational effort. Furthermore, the model captures the component damage states of a CFS partition wall under imposed excitation. This paper first describes damage states of typical CFS partition walls. From the observations of damage mechanism to CFS partition walls subjected to lateral loads, the force–deformation relations of their components are identified by accounting for the initial flexural behavior of studs and followed by the racking behavior of gypsum boards. The interactions between components such as stud-to-track connections are theoretically defined from mechanical properties and geometrical information. To verify the proposed analytical model, two full scale CFS partition walls tested by a quasi-static procedure are introduced. The analytical and experimental results are compared in terms of force–displacement relations, dissipated energy, and the influential damage mechanism of components of the partition walls.

2. Damage Mechanism of CFS Partition Walls

2.1. General Construction Details of CFS Partition Walls

A CFS partition wall generally consists of CFS framing members, and inner and outer wall panels which are made of gypsum boards (GBs). Figure 1 presents the typical Korean building construction practices for CFS partition walls. Top and bottom tracks and vertical studs are used for the CFS framing, and tracks are used to align the vertical studs. Tracks and studs are assembled with powder actuated fasteners (PAFs). GBs used as a sheathing material are attached to the CFS framing with self-drilling metal screws placed at regular intervals. Top and bottom conventional tracks without any vertical slotted holes are anchored to reinforced concrete (RC) slabs by PAFs with a spacing of 600 mm and an edge distance less than 200 mm. Studs are installed between the top and bottom tracks with a spacing of 450 or 600 mm which depends on the dimension of the prefabricated GBs. The length of the studs is determined as 10 mm shorter than the distance between the flanges of top and bottom tracks. After finishing the erection of tracks and studs, 12.5 mm thick GBs are attached to them with metal screws of which the vertical spacing is 300 mm whereas the horizontal spacing of the metal screw depends on that of the studs. A gap of 10 mm between the edge of the GBs and RC slabs provides easy erection and accommodation of their rotational deformation. In order to improve the sound and fire protection capacity of partition walls, the Korean construction practices for CFS walls adopts the installation of double layered GBs consisting of inside and finishing GBs. A finishing GB is nailed after
an inside GB has been attached to studs or tracks. The edge lines of the finishing GB are installed to avoid the overlapping with those of the inside GB.

![Diagram of CFS partition wall](image)

**Figure 1.** Elements and their dimensions of a cold-formed steel (CFS) partition wall erected by typical Korean construction practices.

### 2.2. Typical Damage Mechanism of CFS Partition Walls under Lateral Loads

According to physically observed damages from past earthquakes and failure modes measured from previous experiments [18–22], possible damage of CFS partition walls under lateral loads can be generally categorized. Damage to CFS partition walls typically initiated with screw pop-out at the GBs attached to the top and bottom tracks. In addition, minor damage also occurs in the form of screw pop-out at the wall boundary, and it is then propagated throughout the wall. Minor crushing of GBs occurs at the wall boundary and is followed in the form of major cracks along the GB joints as incipient joint separation of wall intersections occurs. Furthermore, continued joint separation of wall interactions induces GB loosening due to a considerable amount of screw pullthrough at GB boundaries. More excessive damage involves stud deformation and detachment of GBs. Additionally, the transverse wall is damaged as the stiffer in-plane wall is pushed through at higher drift. The damage mechanism at higher drift levels consists of PAF tearing through the tracks or local buckling of the studs. The buckled region forms a plastic hinge at the studs. Regarding this, several studies revealed that the connections of the tracks to the concrete using PAFs and the connections of the tracks to the studs using screws suffer little to no damage [12,21,23–25].

In this study, the damage mechanism of a typical CFS partition wall configured as a floor-to-floor frame system is simply characterized as shown in Figure 2. Predominant damages of CFS partition walls are assumed to be mainly resulted from the racking behavior of GBs subjected to lateral loads. Note that no critical damage occurred at tracks and/or track-to-RC slab connections and the damage on tracks usually occurs when out-of-plane deformation is imposed onto the CFS partition wall, which is out-of-scope of this paper and will not be, therefore, dealt with. CFS framing members possess negligible lateral resistance since their screw connections have minimum rotational stiffness, hence the hinged CFS frame deforms in the shape of a parallelogram. On the other hand, GBs have substantial in-plane rigidity and rotate as a rigid body remaining nearly rectangular in shape [26]. This incompatible deformed shape between the CFS framing and GBs initially induces a displacement demand at the metal screws. The screw’s displacement should be accommodated by a combination of screw tilting and local damage to the GBs. As floor-to-floor relative displacements is increased, similar damage is further developed at higher numbers of screws and GB-to-stud connections. Several screws at the GB-to-CFS framing connections exhibit a variety of damage modes such as tearing and pulling-through. Once the edge of a GB is contacts the RC slab due to the further racking behavior, its corner crushing
is initiated after the gap closing between studs and tracks, and additional axial compression is then imposed to the stud. The damage of studs such as weak axis buckling might be detected when excessive axial force is applied.

\[
\theta = \arctan\left(\frac{\delta_h}{H}\right) \tag{1}
\]

where \( H \) is the height of the CFS partition wall.

Values of \( y_1 \) and \( y_2 \) shown in triangles ② and ③ can be expressed as:

\[
y_1 = \frac{H}{2} \cos \theta = \frac{H}{2} \times \frac{H}{\sqrt{H^2 + \delta_h^2}} \tag{2a}
\]

\[
y_2 = \frac{W}{2} \sin \theta = \frac{W}{2} \times \frac{\delta_h}{\sqrt{H^2 + \delta_h^2}} \tag{2b}
\]

where \( W \) is the width of the GB. The vertical displacement, \( \delta_h \), at the corner of the GB is a relative displacement from the original position \( A \) to the deformed position \( A' \). An ordinate of \( A \) from the

**Figure 2.** Damage mechanism of a typical CFS partition wall.

### 3. Development of the Proposed Analytical Model

#### 3.1. In-Plane Displacements of CFS Partition Walls

When a CFS partition wall exposed is to earthquakes, its in-plane horizontal displacements are mainly dependent on the racking of GBs. To simplify the in-plane displacement of CFS partition walls, the racking behavior can be divided into vertical and horizontal displacements at the corner of GBs. As shown in Figure 3, it is assumed that the GB rotates around its centroid which agrees with that of a connected stud, and the that studs have no initial imperfection. Vertical displacement at the centroid of walls, the racking behavior can be divided into vertical and horizontal displacements at the corner of GBs.
bottom of the partition wall is \( H \) while that of \( A' \) is \( 0.5H + y_1 + y_2 \) shown in triangles \( \circ \) and \( \Diamond \). Finally, the value of \( \delta_v \) due to the racking behavior of a GB can be calculated from:

\[
\delta_v = \left( \frac{H}{2} + y_1 + y_2 \right) - H = \frac{H}{2} + \frac{(H^2 + W\delta_h)}{2\sqrt{H^2 + \delta_h^2}}
\] (3)

In which the racking behavior is represented by the displacement, \( \delta_h \) and the dimensions of the partition wall.

\[ \text{(a) Deformed shape of the GB} \]
\[ \text{(b) Idealized deformations of triangles} \]

\[ \text{(c) Distribution of } \Delta_t \]

Figure 3. Monotonic behavior of a screw connection: (a) deformed shapes of the gypsum board (GB); (b) relative deformation; (c) load-bearing capacity.

3.2. Structural Characteristics of CFS Partition Walls

3.2.1. Screw Connections

Screw connections play an important role determining the initial lateral behavior of a CFS partition wall since the racking behavior results in relative displacements with CFS studs. Relative deformations
at the screw connection can be considered as two different phases: (1) before and (2) after the contact between a GB and an RC slab occurs.

During a displacement, \( \delta_v \) is less than the initial gap, \( g_{gb} \) between the slab and the edge of the GB; relative vertical deformations at the screw connection occur only in the axial direction of a CFS stud. Therefore, \( F_{sc} \) of all the screw connections of a CFS partition wall is derived from the force equilibrium condition indicating that the vertical section sum-of-squares (SRSS) combination.

From the triangle shown at \( \Box \) in Figure 3a, a relative vertical deformation, \( \Delta_{v,i} \) at the top corner of a GB can be computed by:

\[
\Delta_{v,i} = \delta_v (1 / \cos \theta)
\]  

(4)

A relative vertical deformation, \( \Delta_{v,b} \) at the bottom corner of a GB can be presented in triangles \( \Box \) and \( \Box \), and calculated from:

\[
\Delta_{v,b} = (W - w_b) \tan \theta = (W - \Delta_{v,i} / \tan \theta) \tan \theta
\]  

(5)

Then, a relative vertical deformation, \( \Delta_{v,i} \) at the \( i \)th screw connection is calculated under the assumption that the \( \Delta_{v,i} \) is distributed linearly between \( \Delta_{v,i} \) and \( \Delta_{v,b} \):

\[
\Delta_{v,i} = \frac{(\Delta_{v,i} - \Delta_{v,b})}{H} l_i + \Delta_{v,b}
\]  

(6)

where \( l_i \) is the distance of the \( i \)th screw connection from the bottom slab.

If a displacement \( \delta_v \) becomes equal to the initial gap, \( g_{gb} \), \( \Delta_{v,i} \) and \( \Delta_{v,b} \) cannot be increased whereas relative horizontal deformations, \( \Delta_{h,i} \) and \( \Delta_{h,b} \) at the top and bottom corners of a GB are initiated as shown in Figure 3b. With the assumption that relative horizontal deformations, \( \Delta_{h,i} \)s are distributed like the figure, they are determined with the additional horizontal displacement, \( \delta'_h \) occurring after the gap closes:

\[
\Delta_{h,i} = \delta'_h \left( \frac{l_i - H}{2} \right) \cos \theta
\]  

(7)

\[
\delta'_h = \delta_h - \delta_{h, gap, GB}
\]  

(8)

where \( \delta_{h, gap, GB} \) is the horizontal displacement at the initiation of the gap closing. Plugging \( \delta_v = g_{gb} \) into Equation (3) gives:

\[
\left[ (2g_{gb} + H)^2 - W^2 \right] \delta_h^2 - \left( 2H^2W \right) \delta_h + \left[ (2g_{gb} + H)^2 H^2 - H^4 \right] = 0
\]  

(9)

The value of \( \delta_h \) satisfying this quadratic equation becomes \( \delta_{h, gap, GB} \) like the following equation:

\[
\delta_{h, gap, GB} = \frac{H^2W + \sqrt{H^4W^2 - 4g_{gb}H^2(H + g_{gb})[(2g_{gb} + H)^2 - W^2]}}{[(2g_{gb} + H)^2 - W^2]}
\]  

(10)

Based on \( \Delta_{v,i} \) and \( \Delta_{h,i} \) calculated from two different deformation phases of a GB, the total relative deformation, \( \Delta_{l,i} \) of the screw connection is conservatively calculated by the square-root-of-sum-of-squares (SRSS) combination.

As shown in the free body diagram of Figure 3c, the lateral force, \( F_{sc} \) of all the screw connections of a CFS partition wall is derived from the force equilibrium condition indicating that the vertical section locating the screws along with the axial direction of studs might be critical for the racking behavior of GBs. Therefore, \( F_{sc} \) can be obtained from the summation of internal shear forces corresponding to screw tilting and bearing forces, \( f_i \) corresponding to \( \Delta_{l,i} \):

\[
F_{sc} = \left( \frac{W}{H} \right) \sum f_i
\]  

(11)
where the value of $f_i$ utilizes the force–deformation relation which can be fundamentally defined from experimental results of the screw connection.

A partition wall has several screw connections. The force–deformation relation of each screw connection can be divided into three important phases: (1) elastic, (2) tilting, and (3) pull-through phases which are idealized by a tri-linear relation using experimental results. The screw tilting is assumingly initiated at about 75% of the maximum load obtained from experimental results [27]. The bearing capacity of a GB corresponding to the maximum is defined as the initiation of pull-through of the screw. During imposed larger deformations, the load-bearing capacity of the screw connection is degraded and finally the GB completely detaches from the connection where it is remarkably reduced up to 50% of the maximum load. The monotonic behavior and deformed shapes corresponding to phases of each screw connection can be found in the right top figure in Figure 3c.

When imposing the specific value of $\delta_h$ on a partition wall, the relative deformation, $\Delta t_i$, of the $i$th screw connection occurs and varies over its location along the stud, as presented in Figure 3c. With the internal shear force, $f_i$ corresponding to $\Delta t_i$ obtained from the tri-linear force–deformation relation of each screw connection, the force, $F_v$ acting along the axial direction of a stud is obtained by summing $f_i$ of all connections. Considering the force equilibrium condition at the point O in the figure, the lateral force, $F_{SC}$ of all the screw connections of a partition wall is calculated for the imposed specific horizontal displacement. The multi-linear lateral force–displacement relation of the screw connections of the partition wall is finally computed by repeating this series of calculations subjected to the increasing value of the $\delta_h$, as shown in the blackline in the bottom right-hand corner of Figure 3c. For the application of an analytical model, the trilinear lateral force–displacement relation of the screw connections can be simplified, as shown in the red line in the same figure.

### 3.2.2. Gypsum Boards

GBs behave with rigid-body motion and develop no resistance before vertical displacements, $\delta_v$ due to their racking reach to the joint gap size. After $\delta_v$ overcomes the gap size, the behavior of GBs is represented using the contact property with the RC slab. The contact phenomenon is defined by the initial gap, $g_{gb}$ chosen to absorb the construction tolerance of GBs. To derive the contact properties, the critical surface is required to be defined as shown in Figure 4. Since the micro-crack at the GB is initiated from a location where their edge distance is the smallest, the failure surface can be defined as the area including two screw connections installed at the corner of a GB. This kind of corner crushing damage has been observed by many experimental studies which were performed to categorize the damage states of CFS partition walls with typical construction practices. The effective failure area, $A_e$ is calculated by multiplying the corner length, $l_e$ with the thickness, $t$ of a GB. Assuming the corner crushing is concentrated on the effective failure area, the crushing strength of GBs, $f_{gb}$ is calculated as:

$$f_{gb} = N A_e \sigma_b$$  \hspace{1cm} (12)

where $N$ is the number of GBs, and $\sigma_b$ is the compressive strength of the gypsum board material. Using the material test results of GBs [28], $\sigma_b$ is assumed to be 1.48 MPa. Finally, the maximum load-bearing capacity can be obtained from the summation of $f_{gb}$ at expected locations of the corner crushing. The stiffness, $K_{gb}$ and ductility, $\mu_{gb}$ of the GBs are, respectively, defined as 1.4 kN/mm and 5.7, values based on the modelling properties prescribed in ASCE/SEI 41-17 [24]. Therefore, the lateral force, $F_{GB}$ of the GBs due to the contact between the corner of a GB and RC slab is derived from:

$$F_{GB} = K_{gb} (\delta_h - \delta_{h, gap, GB}) \left( F_{GB} \leq \sum f_{gb} \right)$$  \hspace{1cm} (13)
The monotonic behavior of GBs can be idealized to the bi-linear behavior, as presented in Figure 4. Before the closing of the gap between the corner of a GB and a slab where \( \delta_h < \delta_h,\text{gap,GB} \), the resisting force of the GB is not developed. Once \( \delta_h \) reaches \( \delta_h,\text{gap,GB} \), the bearing behavior of the GB is initiated and the lateral force is increased with the stiffness of \( K_{gb} \). After reaching the crushing strength, the lateral force is slightly increased with the post-yield stiffness ratio of 0.01. At larger displacements corresponding to the ductility, \( \mu_{gb} \), strength degradation occurs due to corner crushing of GBs.

### 3.2.3. CFS Studs

Similar to the installation of GBs, there is gap between a CFS stud and a top track for easy erection. The deformation shape and damage of the stud-to-track connection under increasing upward displacements of a stud are presented in Figure 5. Typically, a stud is connected to top and bottom tracks with a single PAF, which develops negligible lateral resistance until the contact shown in the figure occurs. Once the gap, \( g_{st} \), reaches \( \delta_{h,\text{gap,ST}} \), the stud pushes against the track web, which develops the contact mechanism resulting in the local buckling of a CFS stud. Since the stud is enveloped within the sheathing GBs in the out-of-plane direction, its global buckling is restrained in the direction of their strong axis. Torsional buckling in the direction of stud’s weak axis may occur when in-plane deformations are subjected to a CFS partition wall.

### Figure 4. Free-body diagram and monotonic behavior of gypsum boards.

### Figure 5. Determination of monotonic behavior of the stud.

Considering the boundary condition of the stud between screw connections, an unbraced length, \( l_{eff} \) is conservatively assumed to be equal to two times of the screw spacing \( [29] \). The buckling strength of the stud in the in-plane direction, \( f_c \) and its corresponding stiffness, \( K_d \) are, respectively, calculated from:

\[
f_c = \frac{\pi E I}{l_{eff}^2}
\]

(14)
\[ K_a = \frac{EA_{st}}{h} \]  

where \( E \), \( I \), \( A_{st} \), and \( h \) are, respectively, the elastic modulus, the moment of inertia, the area, and the height of a stud. From the force equilibrium of a free-body diagram in Figure 5, the stud located at the edge of a partition wall is critical for the buckling behavior. Lateral force, \( F_{ST} \) of the stud is derived from a bearing force before the buckling, according to the following:

\[
F_{ST} = \left( \frac{W}{H} \right) K_a (\delta_v - g_{st}) = \frac{WK_a}{2} \left[ \frac{(H/\delta_h) + (W/H)}{\sqrt{(H/\delta_h)^2 + 1}} - \frac{2g_{st}}{H} - 1 \right] \left( F_{ST} \leq (W/H)f_c \right)
\]

After the buckling, the residual strength of the stud is assumed to be 30% of \( f_c \), as described in ASCE 41-17 [30].

As shown in the idealized monotonic behavior of a CFS stud at the right figure in Figure 5, when lateral displacements \( \delta_h \) equals to \( \delta_{h,\text{gap,ST}} \), the bearing behavior of the stud is initiated. Applying the additional horizontal displacement, the stud develops elastic behavior with the stiffness of \( K_a \). After the maximum load equal to the buckling capacity of the stud is applied, the lateral force is rapidly degraded to the residual strength level.

3.3. Hysteresis Modelling of CFS Partition Walls

Figure 6 summarizes an entire procedure that can determine the lateral force–displacement relation of a CFS partition wall erected using typical Korean construction details. The flow chart consists of several sub-routines related to the structural behavior of all components in the partition wall: screw connections, GBs, and CFS studs. The procedure starts to compute relative displacements at the corner of GBs and screw connections with input dimensions of the partition wall. With horizontal displacements imposed to the partition wall selected with a sufficiently small value, the sub-routine 1 determines the behaviors of all elements before a gap closing at the corner of GBs. In this step, load-bearing capacities of the partition wall depend on only the behavior of the screw connections. The sub-routine 2 is carried out when the imposed horizontal displacement is larger than \( \delta_{h,\text{gap,GB}} \). The contact properties at the critical surface of GBs are defined in this step. If an imposed horizontal displacement is less than the \( \delta_{h,\text{gap,ST}} \), the sub-routine 3 is carried out where the bearing force of the stud is still not developed. Otherwise, the sub-routine 4 is performed to determine the bearing behavior of the stud. The lateral forces corresponding to the selected horizontal displacement are finally calculated with the sub-routine 5 based on the force equilibrium condition at all the components. Finally, an imposed horizontal displacement is increased and the sub-routines 1 to 5 are iterated until it becomes sufficiently larger than the targeted displacement for the analysis.

This study simplifies the nonlinear hysteretic behavior of a CFS partition wall using discretized lumped springs of influential sub-components, as shown in Figure 7. Three spring assemblies are introduced to represent the hysteresis of the sub-components including studs, screw connections, and GBs which are, respectively, denoted as Element 1, Element 2 and Element 3 in the figure. The monotonic nonlinear behavior of all Elements is described in the previous Sections. Element 1 and Element 3 are constructed with a primary spring and a gap element while Element 2 is made of only a primary spring element. The primary spring in each sub-component is assigned to a one-degree-of-freedom element with zero-length and its backbone curve is adopted from the monotonic force–displacement relations suggested in Figures 3–5. The primary springs are placed at the mid-height of a partition wall and connected to top and bottom RC slabs with rigid links. The springs are implemented to activate in the in-plane direction of a partition wall while its out-of-plane behavior is not considered in this study. Gap elements are including in Element 1 and Element 3 to capture the gap closing at GB-to-RC slab interfaces and stud-to-track connections.
Pinching effects in unloading and reloading are reflected in the hysteresis model of all the screw connections. This study utilizes a well-known Wayne–Stewart model to simulate the cyclic response of all the screw connections including complex pinched hysteretic responses accounting for degradations under cyclic loading as shown in Figure 8. Nine parameters are required to define the Wayne–Stewart model:

- Initial stiffness, $k_0$
- Post-yield stiffness factor, $r_1$
- Post-capping stiffness factor, $r_2$
- Yield strength, $V_y$
- Capping strength, $V'$
- Unloading stiffness factor, $r_{un}$
- Intercept strength, $V_{os}$
- Pinching power factor, $\alpha$
- Softening factor, $\beta$

From the trilinear monotonic curve depicted in Figure 3c, $V'$ and $V_y$ are defined as the maximum load and 75% of $V'$, respectively. The initial and post-yield stiffness are, respectively, used for parameters $k_0$ and $r_1$. In an assumption that load carrying capacity of screw connection has lost in reaching 50% of $V'$, the post-capping stiffness is determined using the ultimate loading state. The parameter $r_{un}$ is assumingly set to 1.0, reflecting the initial unloading stiffness practically equal to the initial stiffness. The intercept strength, $V_{os}$ is calibrated by reflecting the effect of the bearing frame during the experiment. The parameters $\alpha$ of 0.64 and $\beta$ of 1.07 are used for the hysteretic model of the Element 2 representing all the screw connections of a CFS partition wall.
model: initial stiffness, \( k_0 \), post-yield stiffness factor, \( r_1 \), post capping stiffness factor, \( r_2 \), yield strength, \( V'_y \), capping strength, \( V'_y \), unloading stiffness factor, \( r_{un} \), intercept strength, \( V_{un} \), pinching power factor, \( \alpha \), and softening factor, \( \beta \). From the tri-linear monotonic curve depicted in Figure 3c, \( V'_y \) and \( V_y \) are defined as the maximum load and 75\% of \( V'_y \). The initial and post-yield stiffness are, respectively, used for parameters, \( k_0 \) and \( r_1 \). In an assumption that load carrying capacity of screw connection has lost in reaching 50 \% of \( V'_y \), the post-capping stiffness is determined using the ultimate loading state. The parameter, \( r_{un} \) is assumingly set to 1.0, reflecting the initial unloading stiffness practically equal to the initial stiffness. The intercept strength, \( V_{un} \) is calibrated by reflecting the effect of the bearing frame during the experiment. The parameters, \( \alpha \) of 0.64 and \( \beta \) of 1.07 are used for the hysteretic model of the Element 2 representing all the screw connections of a CFS partition wall.

![Figure 8. The hysteresis of the Wayne–Stewart model (from Carr [31]).](image)

4. Validation of the Proposed Analytical Model

4.1. Overview of CFS Partition Wall Experiments and Their Analytical Models

In order to validate the suggested analytical model of CFS partition walls, two full scale specimens were prepared and tested for this study, as shown in Figure 9a. CFS partition wall specimens erected according to the Korean construction practices consist of single bay with 1.8 m of length and 2.1 m of height without return walls at each end. Symbols of ST600 and ST450 shown in Figure 9b were named according to stud spacings of 450 mm and 600 mm of the specimens considered as a main experimental parameter for quasi-static tests. GBs and studs of the specimens were screwed to the top and bottom tracks. To evaluate the drift sensitive partition wall, a quasi-static test loading protocol [32] was used with a total of 15 steps. The loading protocol consisted of repeated cycles of stepwise increasing deformation amplitudes. The first displacement level corresponding to 0.15\% drift ratio was determined as the specimens remain in the elastic range. Other displacement levels consisted of an increase up to 1.4 times the amplitude of previous step. Two cycles were repeated for each amplitude. The maximum displacement level was considered to be 5\% of lateral drift. Figure 10 presents the loading protocol in terms of drift ratios. In order to identify the physically observed damage, visual inspection was carried out after each loading step.
Figure 9. Test specimens: (a) Test setting; (b) Distribution of studs and gypsum boards of ST600 and ST400 specimens.

Figure 10. Loading protocol for the quasi-static loading test.
The analytical models for the specimens were constructed using RUAUMOKO 2D [32]. The material properties of studs were determined from coupon test results [33] and the elastic modulus and yield strength were 208 GPa and 395 MPa, respectively. The structural properties of screw connections erected were determined from test results performed by Choi and Kim [27], of which the specimens had been constructed with two layers of GBs attached to CFS studs with 300 mm spacing of screws, as presented in Figure 11.

![Figure 11](image-url)

**Figure 11.** Material test results of the screw connection (after Choi and Kim [27]): (a) test specimen; (b) test result.
According to the procedure mentioned earlier, the backbone curves of the screw connections, GBs, and studs employed into the specimens were established, as shown in Figure 12. The ST600 and ST450 specimens consist of two GB panels (denoted as GB1 and GB2 in the figure) and three GB panels (denoted as GB3, GB4 and GB5 in the figure), respectively. Each GB panel is comprised of three spring assemblies. For example, the GB1 panel consists of e1, e2 and e3 spring assemblies which represent the screw connections, GBs and studs. Of these spring assemblies, e2 and e3 spring assemblies include the primary spring and contact spring, as mentioned earlier. All three spring assemblies are parallelly-connected in the horizontal direction. For the screw connections, the monotonic behavior of an e1 spring element is obtained from combining the monotonic behaviors of several screw connections comprised of a partition wall. The idealized trilinear curves are then implemented for the e1 spring elements. Gaps are included into the monotonic behaviors of e2 and e3 springs due to the presence of contact elements.

Figure 12. Determination of monotonic behavior of elements consisting of specimens: (a) distribution of elements; (b) backbone curves.
4.2. Validation of the Proposed Analytical Model

4.2.1. Force–displacement Hysteretic Curves Assessment

The analytical models are subjected to the displacement history record that is the same one used for the experiments of the CFS partition wall specimens. Figure 13 comparing the analytical and experimental force–displacement curves shows that the analytical model captures the experimental response such as the overall strength and stiffness degradation and pinching behavior well. The specimens are first loaded in the positive direction, hence the strength capacity of specimens in the negative direction becomes experimentally weaker due to the deteriorations experienced during positive directional loading. Unlike this non-symmetric nature of the experimental results, the suggested analytical model assumes symmetric behavior. Since the construction details, such as gaps between GBs and slabs and studs and runners are hard to exactly relate to those prescribed on the specification, a small variation in force–displacement curves is also inevitably observed. For direction comparison of cycle-by-cycle hysteresis, Figure 14 compares several hysteresis loops of analytical and experimental results of the ST600 and ST450 specimens. The figure confirms that the analysis is in good agreement with the test results.

![Figure 13](image_url)

**Figure 13.** Force–displacement relations of the analytical model and experimental results: (a) ST600; (b) ST450.

![Figure 14](image_url)

**Figure 14.** Cycle-by-cycle comparison between analytical and experimental hysteresis loops: (a) ST600; (b) ST450.
In order to evaluate the variability during the entire loading cycles, a more rigorous error assessment was conducted. Two error indicators are adopted, namely errors in maximum force and in cumulative energy dissipation. Using the maximum force envelop of experiment and analysis as shown in Figure 15, it is observed that the analytical model estimates that the maximum force values show a good agreement for the first two steps of the hysteresis loop. Before contact between GBs and the concrete slab occurs, the estimated maximum forces of the analytical model do not differ more than 10% compared to those of the experimental results. After the eight loading step in which corner crushing of GBs is experimentally initiated, the analytical model estimates the maximum force values in the positive direction of the hysteresis loop with an average error of 11% and more precise estimation is recorded in the negative direction. In particular, due to the contact between studs and tracks, enhanced maximum forces of the ST600 specimen are accurately estimated by the analytical model with an error of 2%.

Figure 15. Comparison of analytical and experimental backbone curves: (a) ST600; (b) ST450.

Figure 16 shows the analytical and experimental cumulative energy dissipated by the specimens. The cumulative energy dissipation obtained from analytical model is slightly underestimated compared to the corresponding experimental results. Since the specimens remain elastic during several initial loading cycles, the model cannot simulate dissipation of energy. However, a small amount of energy dissipation is observed in the experimental results since the friction mechanism could be developed at the test frame. At those displacement ranges, the difference between analytical and experimental results is negligible. The underestimation of the analytical model becomes increased during the last cycles after the maximum force of the screw connections has been reached. This mainly results from the difference of the hysteresis loop in which pinching effects of the screw connection are observed as shown in Figure 14.

Figure 16. Comparison of analytical and experimental cumulative energy dissipation: (a) ST600; (b) ST450.
4.2.2. Damage State Identification

The damage estimated by the analytical model is confirmed in order to validate that the suggested methodology accomplished its objective of predicting the possible damage mechanism of partition walls. Figure 17 compares the estimated damage states in the analytical model with the experimental observations. The initial stiffness reduction in the screw connections is initiated at a 0.5% drift ratio, which is consistent with the observed damages in the experiment where screw tilting first occurred. As drift ratios increase, damaged screws suffered further damage and a higher number of screws were additionally damaged. After the eighth step of loading drift of 2.2%, several screws suffered pullout and pull-through damages to both the ST600 and ST450 specimens. This damage mechanism is also predicted by the analytical model in which the force–displacement relation of the screw connection starts to show strength degradation from the corresponding drift levels.

Figure 17. Comparison of analytical and experimental damage states: (a) ST600; (b) ST450.
Differences of damage to other components between the ST600 and ST450 specimens was negligible. During the tests, crushing or breaking of GBs at the corner of wall panels occurred in both the specimens in drifts ranging from 1.5% to 2.2% corresponding to 50th percentile spots of the GB corners damaged. The predicted damage mechanisms include the interaction between GBs and concrete slabs. The initial gaps of GB-to-slab connections were analytically closed at 1.5% and 2.2% drift ratios and crushing strengths reached at 2.0% and 3.0% drift ratios for the ST600 and ST450 specimens, respectively. Although the analytical model produces a slight difference in the contact initiation, it can reasonably simulate the nonlinearity of the force–displacement relation at the GB-to-slab connection. The analytical model of studies installed in the ST600 specimen captures the interaction of the boundary stud-to-track connection at a 2.5% drift ratio and the bearing strength is developed due to such interaction. Rapid strength degradation in the force–displacement relation occurred at a drift ratio of 3.5% of drift, which resulted from the damage states such as local buckling and bending of studs. These damage mechanisms of studs are consistent with the observed damages in the experiment.

The damage-to-drift correlation obtained from this study is compared to results of previous experimental studies [34,35], of which the specimens were similar to those utilized in this study. As shown in Figure 18, screw tilting and stud buckling were, respectively, observed on 0.40% and 1.9% drift ratios which are almost identical to those measured at the ST600 specimen. The noticeable difference is the occurrence of corner crushing of GBs. The early occurrence of crushing of GBs in this study results in the use of smaller gaps between the edge of GBs and slabs, and between the CFS stud and top tracks than used in the previous studies.

| Damage states   | Screw tilting | Screw pull through | GB corner crushing |
|-----------------|---------------|--------------------|--------------------|
| Drift ratio     | 0.4 %         | 1.9 %              | 2.0 %              |
| Local damage    |               |                    |                    |

Figure 18. Damage-to-drift ratio relation of the reference specimens (from Pali et al. [34], Fiorino et al. [35]).

5. Conclusions

In order to address disadvantages of previously developed macro-models for in-plane deformational CFS partition walls and improve them, this paper proposes an analytical model which can be constructed with a simple modelling procedure capable of tracing the behaviors of GBs, studs and screw connections, and less computational effort with no numerical instability.

From the global in-plane response of a CFS partition wall exposed to earthquakes, the important behavior of each component is identified. Structural properties of screw connection are determined considering two different phases: (1) before and (2) after the contact between a GB and RC slab occurs. The dominant contact phenomenon is utilized to decide structural properties of gypsum boards since friction forces in the interface between their corner and the web of tracks are the only contribution to the global in-plane response of a CFS partition wall. The cyclic response of CFS studs is governed by torsional buckling in the direction of its weak axis. The buckling behavior is used for determining the structural properties of studs. Based on the structural properties of screw connections, GBs, and studs, a procedure in a flow-chart format is suggested to determine the lateral force–displacement relation of a CFS partition wall. The flow chart consists of several sub-routines related to the structural behavior of all components in the partition wall: screw connections, GBs, and CFS studs.

The analysis model constructed with discretized lumped springs of influential sub-components is developed for this study. Three spring assemblies are introduced to represent the hysteresis of the sub-components including studs, screw connections, and GBs. The spring assemblies for studs and
GBs are constructed with a primary spring and a gap element while that for screw connection is made of only a primary spring element.

The suggested analytical model of CFS partition walls is verified with the results obtained from tests of two full scale specimens. The comparison between the analytical and experimental force–displacement curves shows that the analytical model captures the overall strength and stiffness degradation and pinching behavior well. In addition, the estimated damage states in the analytical model are compared with the experimental observations. The initial stiffness reduction and damage propagation of the screw connections and their pullout and pull-through resulting in strength degradation are well predicted by the analytical model. The occurrences of damage, such as crushing or breaking of GBs and buckling of studs, can be properly captured in the proposed model.

The out-of-plane behavior of CFS partition walls might induce detrimental effects on their in-plane behaviors as applied lateral displacements being increased when severe damage to the tracks such as failure of PAFs occurs. Their out-of-plane behavior is mainly governed by the plastic response of the flanges of tracks, which is easily modeled. However, their in-plane behavior is more complicated and is, in turn, difficult analytically model. Therefore, this study focuses on the in-plane behavior of CFS partition walls and develops a macro-modelling approach to capture them only. Nonetheless, pounding effects between out-of-plane and in-plane CFS partition walls are still considered. To address this, further investigating their interaction between out-of-plane and in-plane behaviors of CFS partition walls with additional experimental programs is required and the suggested analytical model could be adjusted by reflecting experimental results.

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