Development of Interaction Diagram for Eccentrically Loaded RC Sandwich Walls with Different Design Parameters

May Haggag, Ezzat H. Fahmy, Mohamed Abdel-Mooty, Sherif Safar

Abstract—Sandwich sections have a very complex nature due to variability of behavior of different materials within the section. Cracking, crushing and yielding capacity of constituent materials enforces high complexity of the section. Furthermore, slippage between the different layers adds to the section complex behavior. Conventional methods implemented in current industrial guidelines do not account for the above complexities. Thus, a throughout study is needed to understand the true behavior of the sandwich panels thus, increase the ability to use them effectively and efficiently. The purpose of this paper is to conduct numerical investigation using ANSYS software for the structural behavior of sandwich wall section under eccentric loading. Sandwich walls studied herein are composed of two RC faces, a foam core and linking shear connectors. Faces are modeled using solid elements and reinforcement together with connectors are modeled using link elements. The analysis conducted herein is nonlinear static analysis incorporating material nonlinearity, crashing and crushing of concrete and yielding of steel. The model is validated by comparing it to test results in literature. After validation, the model is used to establish extensive parametric analysis to investigate the effect of three key parameters on the axial force bending moment interaction diagram of the walls. These parameters are the concrete compressive strength, face thickness and number of shear connectors. Furthermore, the results of the parametric study are used to predict a coefficient that links the interaction diagram of a solid wall to that of a sandwich wall. The equation is predicted using the parametric study data and regression analysis. The predicted α was used to construct the interaction diagram of the investigated wall and the results were compared with ANSYS results and showed good agreement.

Keywords: Sandwich Walls, Interaction Diagrams, Eccentricity, Finite Element Modeling.

I. INTRODUCTION

A. History, Advantages and Types of Sandwich Sections

The use of sandwich structures is increasing dramatically nowadays. This is due to the fact that global warming is becoming more apparent and its effects are becoming more pressuring. Sandwich structures help in saving relatively large amount of money that is otherwise spent on electricity bills (Abdel-Mooty et al, 2012). The second main advantage of sandwich structures is their high performance to weight ratio. Comparing a solid concrete section of thickness d/2 to a sandwich section composing of two surface layers each of

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thickness d/4 at distance d between their centerlines and a very light core layer, both sections have the same width and the same concrete weight. For this example, the sandwich section has 12 times the flexural rigidity of the solid section (DIAB Group 2007).

According to the degree of interaction between the composing layers of the section, sandwich sections are classified into three main types being fully composite, partially composite and non-composite sandwich sections. A fully composite sandwich section acts as a solid section, the two faces and the core deflect together as if they are one layer. In this type of sandwich sections shear is fully transferred between the three layers of the section. The second type of sandwich sections is the partially composite section where partial transfer of shear exists between the section's layers. The type and the amount of shear connectors determine the degree of composite action of the section. The last type of sandwich sections is the non-composite section. Zero degree of composite action exists for this type of section and each layer acts acts independently to carry its share of the applied load.

B. Components of a Sandwich Section

A typical sandwich section is composed of two thin faces and a thick core. The material used in the core is much weaker compared to the faces' material (DIAB Group 2007). To achieve the section's integrity, the three layers are connected by connectors or webs. The face layers of a sandwich wall provide the bending stiffness for the section. The core in a sandwich section has many functions among them is creating enough distance between the faces so that the required flexural rigidity of the section can be attained while providing heat and/or sound insulation. The shear connectors or webs link the entire section together. They have a very important role in preventing local buckling of each individual layer and in transferring shear. Shear connectors are either rectangular regions made of concrete or linking bars that are made of steel or carbon fiber reinforced polymers. The shear connectors can either increase or decrease the conductivity of the section. If concrete regions or steel bars are used they allow the transfer of temperature across the section causing what is called thermal bridges (Abdel-Mooty et al, 2012).

C. Research Objectives and Scope

The previous analytical work done in the field of sandwich wall panels doesn't include investigating the behavior of sandwich walls subjected to combined axial and out of plane lateral loads. Al-Kashif et al. (2012) carried out finite element analysis of flexural loaded sandwich panel. Benayoune et al. (2007) studied numerically the response of sandwich panels to axial loading.

This paper is part of ongoing research that investigates the behavior of eccentrically loaded reinforced concrete sandwich walls with eccentricity ranging from 0.06 m to 0.43 m. The effect of three very important parameters on the behavior of the sandwich walls are tested. These parameters are the compressive strength of the concrete, the face layer thickness, and the number of shear connectors. The effect of each of the parameters is depicted by comparing the interaction diagrams of the different walls.

In this paper a coefficient α is predicted which correlates the interaction diagram of a sandwich wall from that of a solid wall with the same total thickness. The equation of coefficient α is predicted using regression analysis. After that α is used together with the solid walls interaction diagrams obtained using ANSYS analysis to predict sandwich walls interaction diagrams. Finally, to test the prediction of α , the interaction diagrams obtained using ANSYS and the ones predicted are compared.

II. FINITE ELEMENT MODELING OF SANDWICH WALLS

The sandwich walls are modeled and analyzed using finite elements method. The commercial finite elements analysis software ANSYS is used in the present investigation. ANYSY software allows for the construction of computer models of structures and the application of design loads and other design criteria. It allows for the study of structural response of the model including stress and strain levels, temperature distributions, pressure, etc. ANSYS also accommodates material nonlinearity, crushing and crashing of concrete and yielding of steel.

A total of 39 walls were modeled in this study. Three solid walls were modeled with compressive strengths 25 MPa, 36 MPa and 45 MPa. Thirty six sandwich walls were modeled with variable face layer thickness, number of connecting webs and concrete compressive strength as per Figure 1. The concrete webs thickness was kept as 100 mm and the core was selected to be foam and thus it was not modeled. For the solid walls modeled, the coding comprises "S" for solid wall followed by compressive strength value. Sandwich wall coding is done by listing the number of connecting webs (shear connectors) followed by the face layer thickness then the concrete compressive strength.
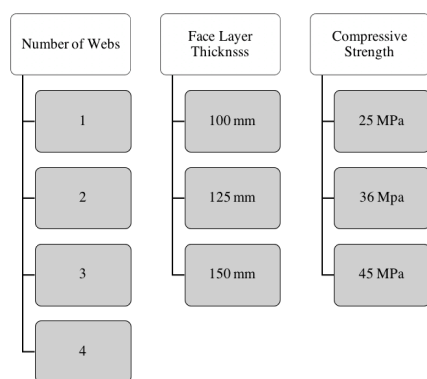

Fig.1. Sandwich Wall Parameters

The walls modeled are of 3000 mm height, 3000 mm width, and 350 mm thickness. The thickness of the two reinforced concrete faces is varied and the core thickness is also varied

to achieve the 350 mm total wall thickness. As for the web locations in sandwich walls, all webs are located at equal span. Figure 2 shows the section and elevation for the sandwich wall with four webs.
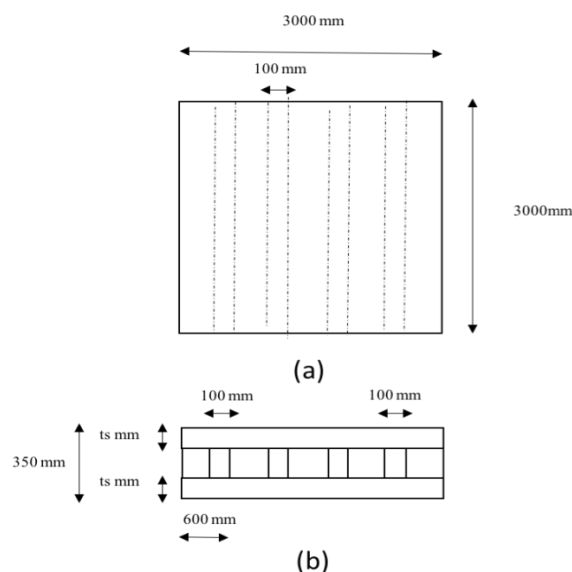

Fig. 2. Four Webs Sandwich Wall Elevation (a) and Section (b)

To achieve uniform displacement of top nodes, a 100 mm rigid steel beam was added at the top of the wall. Also, the bottom of the walls was fixed to achieve proper support fixation. A steel mesh of 8Φ13 and 7Φ10 is put in each concrete face. The shear connecters reinforcing steel bars which are Φ10 are linked to the steel meshes in the faces.

The wall is restrained in x, y and z directions at the bottom to represent fixed support condition. While at the top it is restrained in the x direction to represent testing condition. As for the applied loads they are applied as displacements. The displacements are applied on the top nodes in both axial direction and out of plane directions. The lateral displacement is always applied as ratio of the axial displacement to represent eccentricity. For each wall model three ratios of lateral to axial displacements were selected which are 5, 10 and 30 to depict three points on the interaction diagram.

The analysis conducted by ANSYS is small displacement nonlinear static analysis. The model nonlinearity evolves from nonlinearity of material. The convergence criteria are left as the default of the program. As for the number of sub-steps, it is changed for each run until reaching the maximum convergence limit possible.

III. FINITE ELEMENT MODEL PARAMETERS

The main parameters of any ANSYS model are element types, material properties, element sizes and boundary conditions.

A. Element Types

The reinforced concrete faces are modeled with Solid65. The solid is capable of accommodating cracking in tension and crushing in compression while the steel bars are modeled with Link8. This three-dimensional element is a uniaxial tension-compression element. The steel beam on top of the wall is modeled with solid 46. Solid45 has

plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities.

B. Material Properties

The compressive strength of the concrete f_{cu} and tensile strength f_r are governed by the Equations 1 and 2 (Kachlakev et al, 2001).

$$f_{cu} = \left(\frac{E}{5700}\right)^2 \tag{1}$$

$$f_r = 7.5\sqrt{f_{cu}} \tag{2}$$

Where, E is the material modulus of elasticity and f_{cu}, f_r and E are in psi. These were converted to SI units to be used in the model. The compressive stress strain relationship for concrete is derived using Equations 3, 4 and 5.

$$f = \frac{E\varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_o}\right)^2}$$

$$f = \frac{E\varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_o}\right)^2} \tag{3}$$

$$\varepsilon_o = \frac{2f_{cu}}{E} \tag{4}$$

$$[5] \quad E = \frac{f}{\varepsilon}\varepsilon_o = \frac{2fc}{E}$$

$$E = \frac{f}{\varepsilon}$$

Where, ε is the strain at a given f and ε_o is the strain at the ultimate stress.

The theoretical stress strain curve of concrete is calculated and inserted in the model. Poisson's ratio ν is assumed to be 0.2. Shear transfer coefficient represents conditions of the cracked face. It's a number that varies between 0 in case of a very smooth crack representing the total loss of shear and 1 for a rough crack representing no loss of shear. For reinforced concrete structures open crack shear coefficient varies between 0.05 and 0.25, in the present work it is taken as 0.2. Closed crack shear coefficient varies between 0.7 and 0.9 and is considered in the present work as 0.9. The rebar ratio is kept as default in the concrete faces and connecting webs because the steel bars are modeled as link 8 elements and not smeared into the concrete.

The steel bars are modeled as bilinear isotropic hardening materials. The modulus of elasticity of steel was assumed to be 200 GPa. The yield stress was assumed to be 400 MPa and Poisson's ratio was assumed to be 0.3. Tangent modulus was assumed to be 20. The stress strain relationship of steel is assumed to be identical l in tension and compression. Finally, the steel beam on top of the wall is modeled as linear elastic material with modulus of elasticity equals to 200 GPa and Possion's ratio of 0.3.

C. Element Sizes

For the concrete faces the, mesh is created in a way as to link the nodes in the concrete to the nodes in the reinforcing steel bars so the concrete and steel behave as one unit. The element sizes in the model are selected so that they are not large enough to cause inaccurate results and not too small to cause complications while running the model. Elements were chosen to be 100 mm by 100 mm except for the elements near the shear connectors which were chosen to be 50 mm by 50 mm. Figure 3 shows the elements meshing.
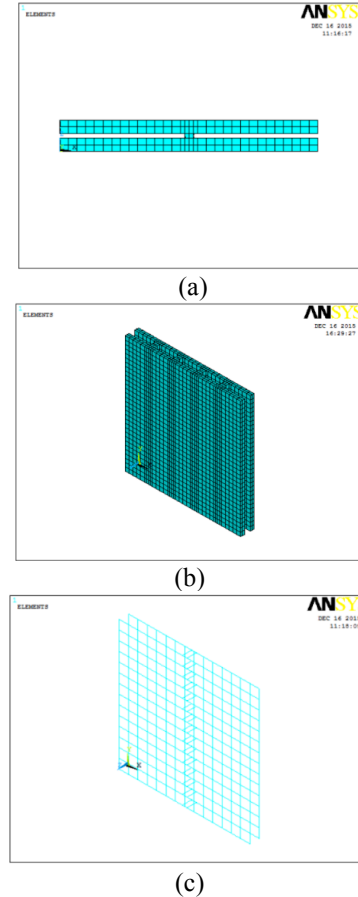

(a)

(b)

(c)

Fig. 3. Element Meshing (a) Concrete Section, (b) Concrete Elevation and (c) Steel Bars Elevation

IV. FINITE ELEMENT MODEL VALIDATION

The model is validated using experimental work in literature. A finite element model is constructed to simulate the ferrocement sandwich wall tested by Gaafar (2004) under concentric axial load. Validating the model against axially loaded wall is selected because there is no research found in the literature that applies range of eccentric loading close to the range specified herein. Gaafar's sandwich walls consist of two thin ferrocement layers reinforced with steel mesh and an autoclaved aerated lightweight concrete brick core. The panel size is 380 mm width by 1000 mm height. Gaafar's experimental work resulted in ultimate axial load of 415 kN while the model has 437.14 kN ultimate axial load resulting in an error of 5.3% which is considered acceptable. Also the cracking pattern was shown to be almost identical experimentally and numerically. This is considered as a sound validation for the numerical model.

V. FINITE ELEMENT MODEL RESULTS

A. Sample of Parametric Study Results for Sandwich Wells

The interaction diagram between the applied axial force and the bending moment is drawn for each studied wall

including the solid walls modeled. 108 computer runs for the sandwich walls in addition to 9 runs for the solid walls were performed using ANSYS finite element program. To be able to correlate the walls and analyze the effect of each parameter on its own, three clusters were created each one involving one of the parameters studied, which are:

Effect of fcu (ts and n are kept constant while fcu is varied).
Effect of ts (fcu and n are kept constant while ts is varied).
Effect of n (fcu and ts are kept constant while n is varied).

As a sample of the analysis, to depict the effect of number of webs or connectors on interaction relationship of the walls with 125 mm face layer thickness and 36 MPa concrete compressive strength Figure 4 is shown herein. It can be seen that the interaction diagram of wall 212536 was shifted by 74% while the interaction diagram of wall 312536 shifted by 106% and the interaction diagram of wall 412536 was shifted by 128% from that of wall 112536 at 0.15 m eccentricity. The balanced section was found at eccentricity 0.15 m, 0.21 m, 0.21 m and 0.24 m for walls 112536, 212536, 312536 and 412536 respectively.

Considering the point on the curve representing the balanced section, the increase in axial force and bending moment can be seen in Figure 5. This shows that when the number of shear connectors increases the percentage of increase in bending moment is much more than the increase in axial force. Also, it can be seen that the maximum percentage of increase in bending moment occurred is when the number of shear connectors is changed from 1 to 2.

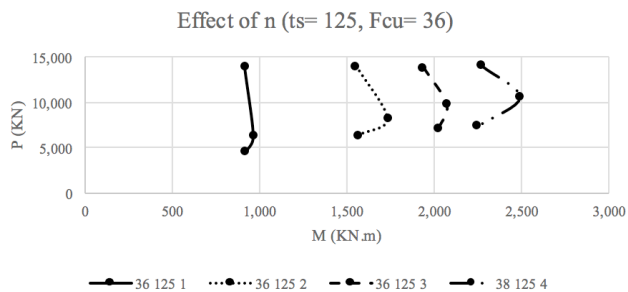The rest of the comprehensive parametric study results and analysis are presented in Haggag (2016).
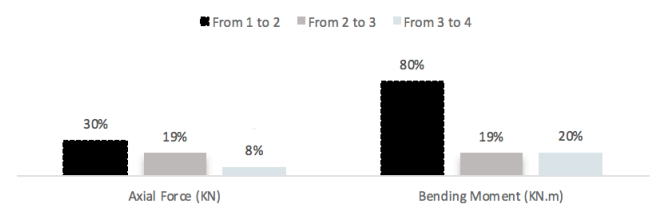

Fig, 4. Effect of n (ts= 125, fcu= 36)

Fig. 5. Axial Force and Bending Moment Comparison for Walls with ts=125 and fcu= 36

B. Comparison of Sandwich and Solid Walls Results

To understand the behavior of sandwich walls in comparison with solid walls and to capture the effect of changing sandwich wall parameters the axial force and bending moment capacity of some sandwich walls are compared to those of the solid walls while varying wall parameters. It was observed that the percent of sandwich walls to solid walls axial force and bending moment increases drastically as the number of webs increases varying from 34% for the 1 web wall to 84% for the 4 webs for walls with compressive strength 25 MPa and face thickness 100 mm. Furthermore, it was observed that the percent of sandwich walls to solid walls axial force and bending moment varies slightly (in a range of about 6%) as the compressive strength increases from 25 MPa to 45 MPa regardless of the face thickness and the number of webs. Finally, it was observed that the percent of sandwich walls to solid walls axial force and bending moment is almost constant as the face thickness increases for walls with compressive strength 45 MPa and 4 webs.

This shows that the increase in the number of webs is the most effective parameter in increasing the sandwich wall capacity with respect to the solid wall compared to increasing the compressive strength or the face layer thickness. The results also show that for all compressive strengths and the face layer thicknesses, the most increase in axial and bending moment capacities of sandwich compared to solid walls happened when the number of webs increased from 1 to 2. As the number of webs increased to 3 or 4 the capacity still increased but at a slower rate. Finally, the 4 web walls with any face thickness and compressive strength proved to have axial and bending capacities very close to those of the solid wall with the same total thickness.

VI. CORRELATION BETWEEN SANDWICH AND SOLID WALLS INTERACTION DIAGRAMS

A. Predicted of Coefficient α

The proposed coefficient α for correlating the axial force (P) and bending moment (M) for the sandwich wall to those of the solid wall (Po and Mo) at the same eccentricity ratio (e/t) is calculated using the data obtained from solid and sandwich walls models. The values of P and M were obtained from interaction diagram for each sandwich wall while the values Po and Mo were obtained from the interaction diagram for the corresponding solid wall as obtained from ANSYS results at the same eccentricity ratio (e/t). Based on the analysis conducted, It was concluded that the main parameters affecting the coefficient α are: 1) the eccentricity ratio (e/t) where e is the eccentricity (M/P) and t is the total wall thickness, 2) the ratio of the sum of face layers thickness to the total wall thickness (2 ts /t) where (ts) is the face layer thickness, 3) the ratio of the total webs thickness to the wall width (n tw/ w) where n is the number of webs, tw is the web thickness, and w is the wall width, 4) the ratio of the concrete compressive strength fcu to the reinforcing steel yield stress fy.

Multiple linear regression was performed using EXCEL LINEST function. The LINEST function performs either single or multiple linear regression. It calculates the statistics for a line by using the least squares method. Due to the complicated relationship between the variables, the relationship between the dependent and independent variables (e/t, 2ts/t, n tw/w, and fcu/fy) was assumed to be nonlinear.

To be able to carry out the multiple nonlinear regression using the LINEST function the equation predicted by EXCEL is first assumed to be linear in terms of linear logarithm equation and after prediction it is transformed by

using logarithmic rules to be nonlinear power equation. Equations 5 and 6 show the logarithmic rules used to transform linear logarithmic equation 7 to nonlinear power equations 8.

$$\log(ab) = \log(a) + \log(b) \tag{5}$$

$$\log(a)^b = b\log(a) \tag{6}$$

$$\log(a_p) = \log(a) + b\log\left(\frac{e}{t}\right) + c\log\left(\frac{2t_s}{t}\right)$$
$$+ d\log\left(\frac{100n}{w}\right) + e\log\left(\frac{f_{cu}}{f_y}\right) \tag{7}$$

$$\alpha_p = a\left(\frac{e}{t}\right)^b\left(\frac{2t_s}{t}\right)^c\left(\frac{100n}{w}\right)^d\left(\frac{f_{cu}}{f_y}\right)^e \tag{8}$$

The values obtained from the multiple linear regression for the constants a, b, c, d, and e are 2.34, -0.15, 0.56, 0,57 and -0.12 respectively. Accordingly, the proposed coefficient α_p is predicted as per Equation 9.

$$\alpha_p = a\left(\frac{e}{t}\right)^b\left(\frac{2t_s}{t}\right)^c\left(\frac{100n}{w}\right)^d\left(\frac{f_{cu}}{f_y}\right)^e \tag{9}$$

The r2 value for this prediction equation was obtained as 0.89. When α was predicted using Equation 10, 86% of the predicted points lied within ± 15% error from those calculated from ANSYS analysis.

B. Calculation of Predicted Axial Force and Bending Moment

Using Equation 9, the coefficient αp was predicted for each wall designation according to its pertinent four parameters e/t, (2ts /t), (n tw/ w), and (fcu/fy). Then using the solid walls data which was obtained earlier from ANSY for the corresponding fcu, the predicted axial force Pp and the predicted bending moment Mp for each sandwich were calculated using the relations:

$$K_t = \left(1 - \frac{R^2\tau}{c_a + v\tan\delta}\right)^4 k_1 \tag{10}$$

$$K_t = \left(1 - \frac{R^2\tau}{c_a + v\tan\delta}\right)^4 k_1 \tag{11}$$

The predicted axial forces (Pp) are plotted in Figure 6 against those obtained from ANSYS analysis to illustrate the spreading of the points about the 45 degree line which represents 100% accuracy in predicting the axial force. Figure 7 shows the plotted Mp against M from ANSYS analysis. The trend line for both set of points almost coincided with the 45-degree line with r2 of 0.93.
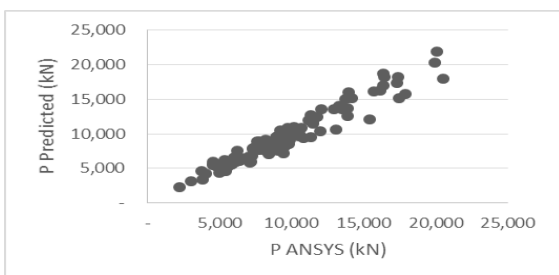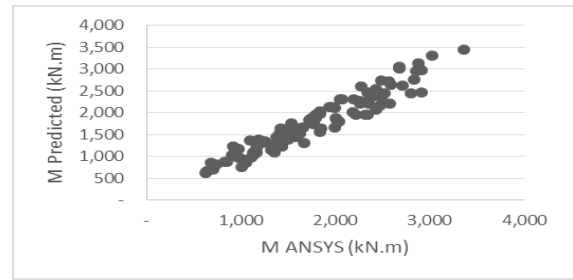

Fig, 6. Axial Force Predicted vs. Calculated

Fig. 7. Bending Moment Predicted vs. Calculated

C. Comparison of Obtained and Predicted Interaction Diagrams

The obtained interaction diagrams from ANSYS analysis for the three solid walls S25, S36, and S45 were used to predict the interaction diagram for each of the analyzed sandwich walls. The eccentricity ratio (e/t) at each of the four plotted points for each diagram was determined and was used together with the pertinent (2ts /t), (n tw/ w), and (fcu/ fy) to determine αp for one point on the interaction diagram for each wall. The process was repeated for the four plotted points to obtain four corresponding points on the predicted interaction diagram.

The predicted interaction diagrams were drawn against the ones obtained from ANSYS for the analyzed 36 different walls. Figure 8 through 10 show samples of these curves. Figure 8 shows the comparison for walls with 100 mm face layer thickness and 25 MPa compressive strength and variable number of webs. While figure 9 shows the comparison for walls with 125 mm face layer thickness and 36 MPa compressive strength and variable number of webs. Finally, figure 10 shows the comparison for walls with 150 mm face layer thickness and 45 MPa compressive strength and variable number of webs.

The majority of the data points followed the trend of the corresponding interaction diagram within the range of error of ± 15% as stated before for the prediction of the coefficient α.
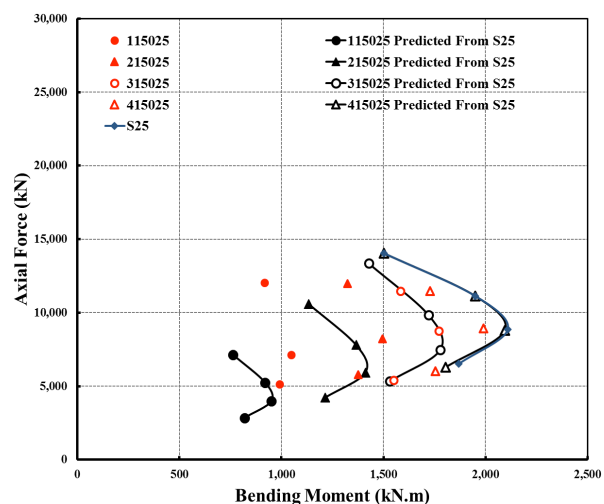

Fig. 8. Interaction Relationship Calculated vs. Predicted (fcu=45 and ts=150)
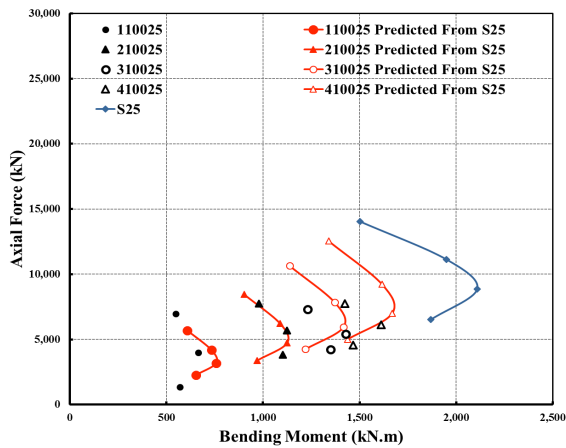
Fig. 9. Interaction Relationship Calculated vs. Predicted (fcu =25 and ts=100)

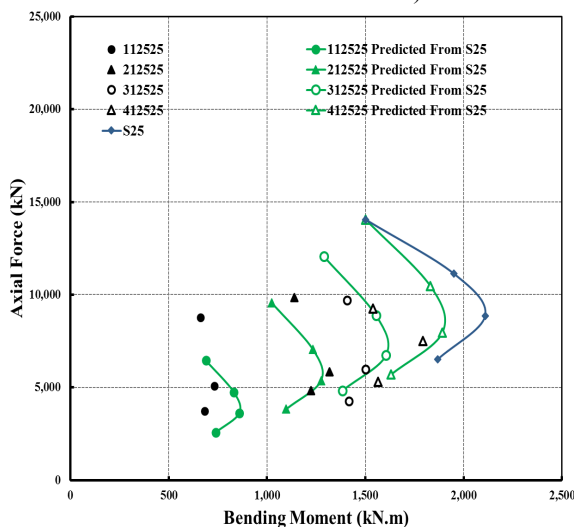
Fig. 10. Interaction Relationship Calculated vs. Predicted (fcu=25 and ts=125)

VII. CONCLUSIONS

Based on the results of the analysis presented in this paper, the following main conclusions can be drawn:

• The predicted α was used to construct the interaction diagrams of the investigated walls and the results were compared with ANSYS results and showed good agreement.

• As the compressive strength increases the axial and bending capacity of the sandwich wall increase regardless of the number of web connectors or the face thickness. The rate of increase varies as the number of web connectors and face thickness are changed.

• As the face thickness increases the axial and bending capacity of the sandwich wall increase regardless of the number of web connectors or the compressive strength. The rate of increase varies as the number of web connectors and compressive strength is changed.

• As the number of web connectors increases the axial and bending capacity of the sandwich wall increase regardless of the face thickness or the compressive strength. The rate of increase varies as the face thickness and compressive strength are changed.

• The percent of sandwich walls to solid walls axial force and bending moment increases drastically as the number of webs increases varying from about 30% for the 1 web walls to almost 90% for the 4 webs walls.

• Unlike the number of webs, increasing concrete compressive strength or face layer thickness doesn't affect the percent of sandwich walls to solid walls axial force and bending moment.

• The use of one shear connector guarantees a minimum of about 30% and a maximum of about 65% sandwich to solid wall axial force and bending moment depending on the sandwich wall concrete compressive strength, face thickness and load eccentricity.

• The use of two shear connectors guarantees a minimum of about 50% and a maximum of about 90% sandwich to solid wall axial force and bending moment depending on the sandwich wall concrete compressive strength, face thickness and load eccentricity.

• The use of three shear connectors guarantees a minimum of about 65% and a maximum of about 90% sandwich to solid wall axial force and bending moment depending on the sandwich wall concrete compressive strength, face thickness and load eccentricity.

• The use of four shear connectors guarantees a minimum of about 70% and a maximum of about 100% sandwich to solid wall axial force and bending moment depending on the sandwich wall concrete compressive strength, face thickness and load eccentricity.

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