Finite Element Based Analysis and Design of Sandwich Panel Structures

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Abstract

There have been several developments in the use of thin-wall concrete or mortar based elements and components for the construction of various types of buildings and structures. One of these systems is the sandwich panels, consisting of two concrete/ferrocement surfaces, separated by a layer of fill material, typically polystyrene. This sandwich panel is often constructed in two stages. First, the panel skeletons, made of layers of wire-mesh separated by polystyrene sheet are pre-assembled in factory or shop. In second stage there panels are placed side by side to form the required enclosures and forms, and then shortcrete, or hand plastering is applied over the wire mesh to complete the construction. After curing and hardening, this results in a fairly stiff structural system with excellent insulation properties.

This paper describes the evaluation and application of this system to a residential building, based on laboratory testing of components and sub-systems and finite element based analysis, using the results obtained from the testing. Special emphasis is placed on the seismic response.

Keywords

Ferrocement, Polystyrene, Sandwich Panels, Thin-Wall concrete, Finite Element Analysis.

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1. Introduction

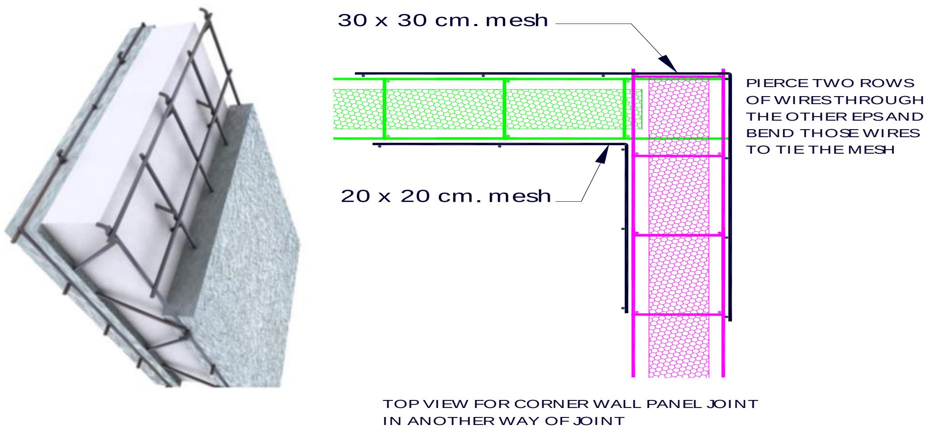
There have been several developments in the use of thin-wall concrete or mortar based elements and components for the construction of various types of buildings and structures. One of these systems is the sandwich panels, consisting of two concrete/ferrocement surfaces, separated by a layer of fill material, typically polystyrene. This sandwich panel is often constructed in two stages. First, the panel skeletons, made of layers of wire-mesh separated by polystyrene sheet are pre-assembled in factory or shop. In second stage there panels are placed side by side to form the required enclosures and forms, and then shortcrete, or hand plastering is applied over the wire mesh to complete the construction. After curing and hardening, this results in a fairly stiff structural system with excellent insulation properties.

This paper present the research carried out to apply this technology and system for the design of single and double story structure for residential and office use. The research consisted of laboratory testing of the sandwich panels to determine the basic properties and behavior, using FEM based procedure to model, analyze and design the structural systems, with special focus on the seismic resistance.

1.1 Sandwich Panel System

The basic system studied in the current research consists of two Ferro cement/ concrete layers of 40 mm to 60 mm thickness reinforced by wire mesh of typically 50 mm spacing. The inner core consists of polystyrene sheet of thickness that can be varied to obtain the desired total thickness. The total thickness of sandwich panel ranges from 100 – 180 mm. The two outer wire mess are connected by trussed wire at regular interval, passing through the foam to create a composite system. The thickness of the wires used for outer mesh, as well as for the interconnecting truss can be varied to obtain the desired strength and stiffness properties

This sandwich panel is used for walls, slabs and roof while ordinary reinforced concrete structure is used in some part of the building as required. Rebar dia 9 mm @300 mm is added at bottom concrete layer for slab panel to carry gravity loads. All panels are connected by using dowel bars. Concrete or mortar spraying method is used with temporary support to cast this panel system.



(a) (b)

Figure 2—a) 3D Section of the sandwich panel; and b) Sample of connection details between panels

2. The Overall Research Plan

The overall research plan is shown in Figure 1. It can be seen from the figure that the actual residential building design requirements, combined with the applicable demands and requirements for local conditions were incorporated to create comprehensive finite element based models. The properties and acceptance criteria for the structure material and components are derived and determined from the laboratory tests and integrated into the analysis to produce the recommended design details and specifications. This approach ensures that unique and specific features, as well as behavior of the system are used for the Finite Element Analysis.

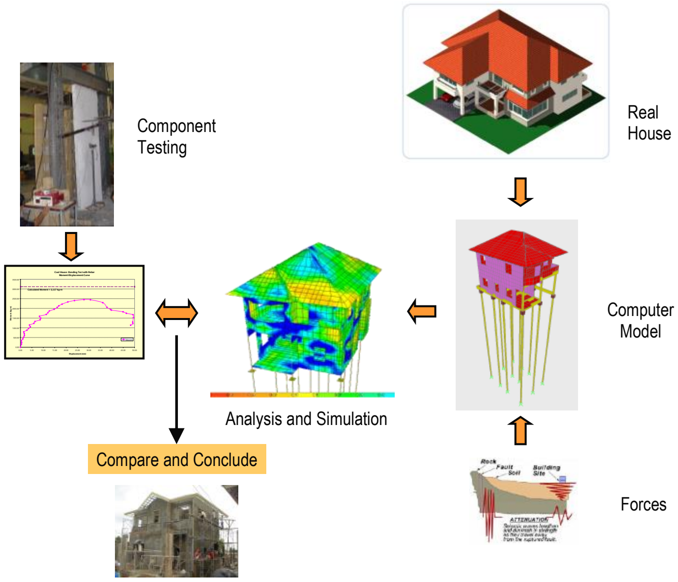


Figure 1- The Overview of research process

3. Laboratory Testing.

A comprehensive test plan was formulated to provide basic information and understanding for proper and effective FEA based modeling and analysis carried out subsequently. The testing was planned to provide answers to the questions: (a) do the two outer concrete layers and the inner foam layer really behave as a single composite material, (b) determine the equivalent stiffness properties of the sandwich panel that can be used for the purpose of modeling. (c) Obtain the strength capacities of the panels in various directions of loading and deformations to compute D/C ratio and to develop acceptance criterion. (d) the capacities of the connections and joints of the system component between each other and with the foundation.

(e) the susceptibly and degradation of the panels subjected to in-plane cyclic loads. The following tests were carried out.

The basic test-setup and the key results obtained from the testing are shown in table 1. The tests were carried out at the Structural Engineers Laboration at the School of Engineering and Technology, Asian Institute of Technology, Thailand.

Table 1—Overview of static loading tests

Test No.	Panel Type	Loading Type	Objectives
1	Slab Panel without Rebar	Static Load	To study bending capacity
2	Slab Panel with Rebar	Static Load	To study bending capacity
3	Wall Panel	Static Axial Load	To study axial load capacity
4	Wall Panel	Static In-Plane Load	To study connectivity between two concrete layers

3.1 Bending Test on slab without rebars

To determine the flexure response for use of panels as slabs and walls subjected to out-of plane loads. This test demonstrated that the sandwich panel behaved similar to a normal composite reinforced concrete section. In this test no additional rebars were added.

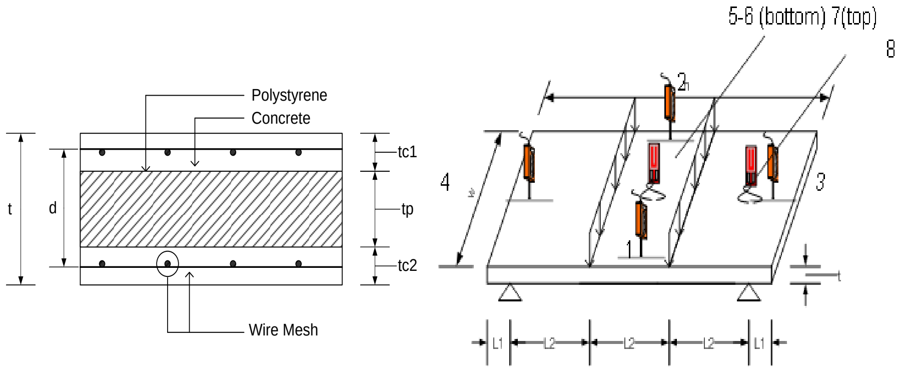
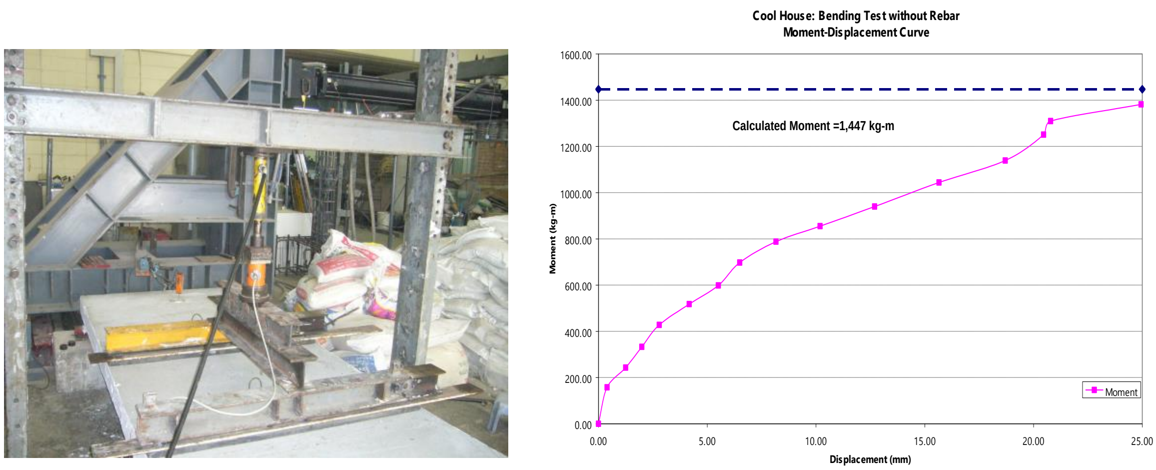


Figure 3 -- Test No 1- Bending Test Setup and Cross Section Details



(a) (b)

Figure 4 – a) Static Bending test of slab without rebar; and b) Test Result; Moment and Deflection relationship.

3.2 Bending test on slab with rebar

This test was carried out to determine the effectiveness of the truss wire to retain the integrity of the sandwich panel. Additional rebars were added to study the improvement in flexural capacity, needed for use on slab panels.

3.3 Axial Load Test

This was conducted to determine the axial load response for using the panels as load bearing walls. This also helped to determine bucking load for the wall units. In-Plane Cyclic Load Test: This test was conducted to determine the in-plane response of the panels cyclic loads, typically imposed on the walls due to seismic excitation. This test was crucial to get an inculcation of linear and non-linear characteristic for seismic capacity evaluation.

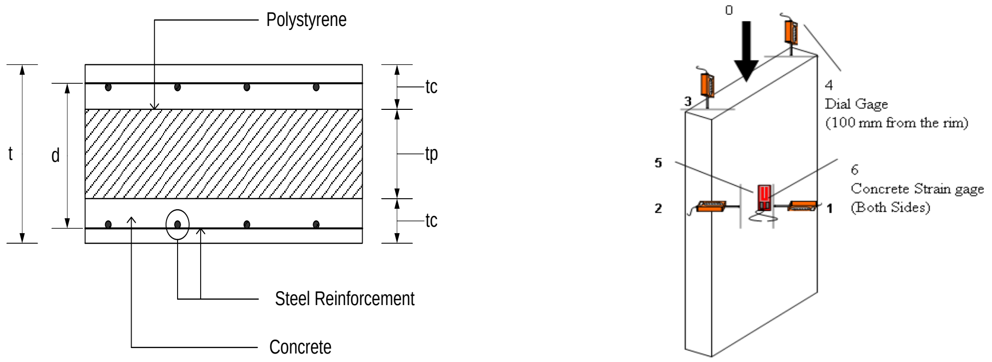
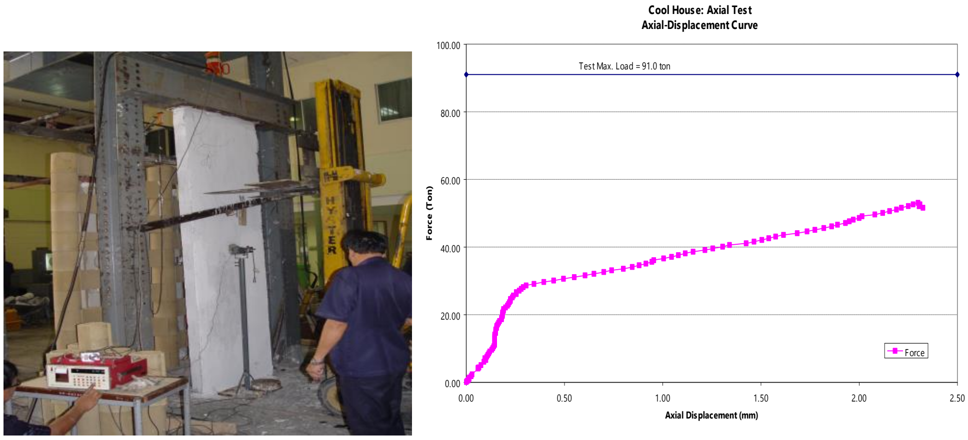


Figure 5 – Test no 3 Axial load setup and cross section details



(a) (b)

Figure 6 – a) Test No 3: Axial load test on single wall: and b) Test result; Axial force and displacement diagram

3.4 In plane Shear Test

The objective of this test is to study connectivity of two parallel panels and find out the maximum in-plane shear capacity.

Although this was indirectly demonstrated by the flexural bending test, a further direct shear loading test was conducted to confirm the resistance to such forces.

4. Finite Element based Analysis and Design

It was considered important that a fairly comprehensive modeling approach be used to determine the response of the sample structure, with minimal assumptions and simplifications so that the results obtained from the testing can be used effectively and not be lost or diluted due to modeling complications.

4.1 The Representative 2-Story Residential Building

Finite element models were created from architectural drawing of 2-story building provided by the client. This building contains three bedrooms, two toilets, one living room, one kitchen and one dining room. Total usage area is around 120 square-meters. All walls, slabs at 2nd floor and roofs are built of sandwich panel. Ordinary RC structure was used for beams, columns and slabs at 1st floor. Due to the lack of structural drawings provided by the client, all structural component information and location were assumed based on typical standard used in Thailand. Details of Architectural drawings for this building are shown in the following figures.

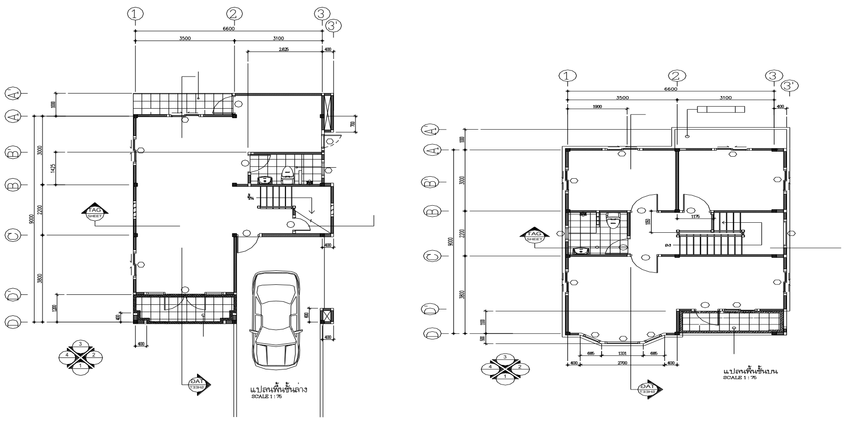


Figure 7—First floor and Second floor plan

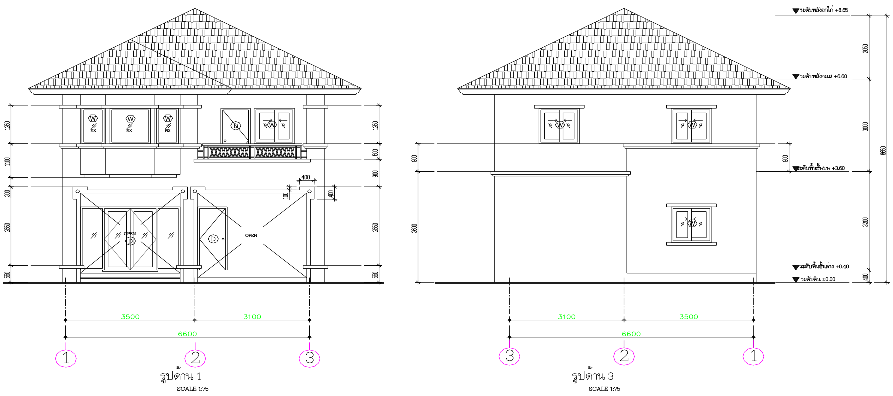


Figure 8-- Front and Back Elevations

4.2 Analysis Methodology

A comprehensive modeling and analysis of the structure and its components under study were carried out with an objective to understand the behavior of the structure, to replicate and predict its response to various possible loads including earthquake, and to evaluate the safety and serviceability states. A full three dimensional, finite element model of the two- story building and associated components were constructed by using appropriate finite element software. Series of linear and nonlinear as well as static and dynamic analyses were carried out for various objectives.

4.3 Finite Element Model

Three full three-dimensional finite element models of the structural system were created from architectural drawings provided by client using SAP2000. All three finite element models comprise of shell and frame element to represent structural components. Model 1 was created to represent the building resting on pile system on soft soil. Response spectrums, defined in UBC97 code and those defined for Bangkok, were applied to this model for seismic analysis. After comparing the analysis results from UBC97 spectrum and Bangkok spectrum with properties obtained from laboratory test results, it is found that in-plane shear in some isolated locations using UBC97 spectrum is more than the capacity determined from the laboratory test. Model 2 was created to solve this problem by adding two extra wall panels in the 1st floor of car parking area in the original model to reduce the in-plane shear distribution and convert this car parking area to living room area. Model 3 was created using modified 1st floor plan layout from model 2 and using spring support to represent the isolated footing, typically used in northern Thailand

Table 2 -- Structural Component and Finite Element Model

Structural Component	Finite Element Model
Supports	- Hinge Support at Pile Tip - Spring along Pile Length - Spring for Isolated Footing
Piles	Frame Element
Pile caps	Shell Element
Columns	Frame Element
Beams	Frame Element
Cast-in-Place Slabs	Shell Element
Sandwich Panel Slabs	Shell Element
Sandwich Panel Walls	Shell Element
Roof	Shell Element

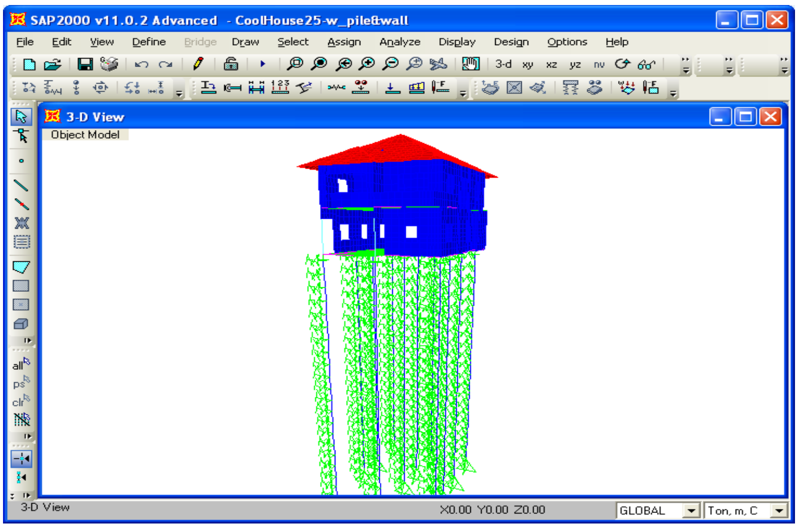


Figure 9 – Model 2 with piles and extra walls

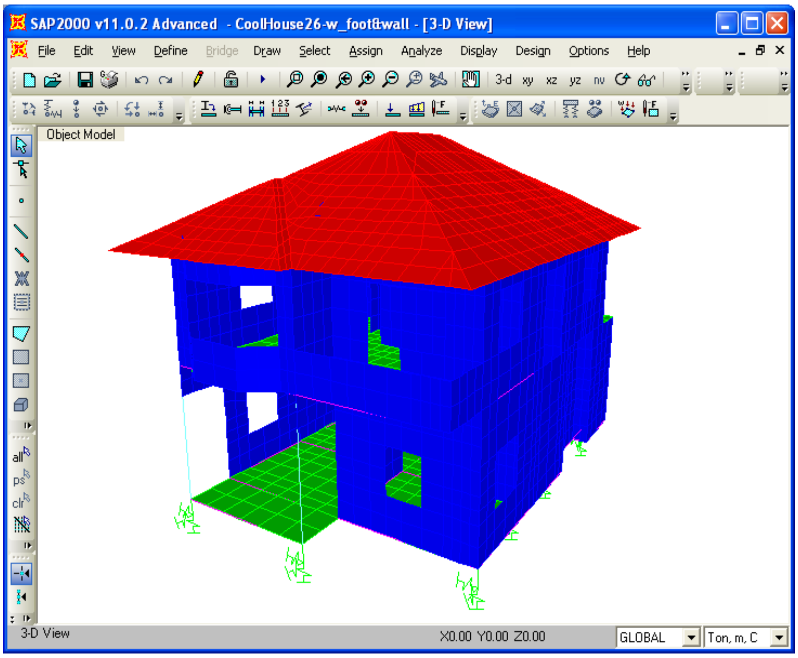


Figure 10 – Model 3 with piles and extra walls

4.4 Earthquake Load

Response spectrum analysis with appropriate response spectrum curve was performed in all models to evaluate the response of the building under earthquake load. For Model 1, Bangkok response spectrum curve was used for possible earthquake on special Bangkok soil as shown in the following figure. For Model 2, the response spectrum curve based on UBC 97 for Zone 2B with soil type SE is used to analyze the structure under possible earthquake in soft soil for the area outside Bangkok. For Model 3, the response spectrum curve based on UBC 97 for Zone 2B and soil type SD is used to analyze the structure under possible earthquake in stiff soil for the area outside Bangkok as shown in the following figure.

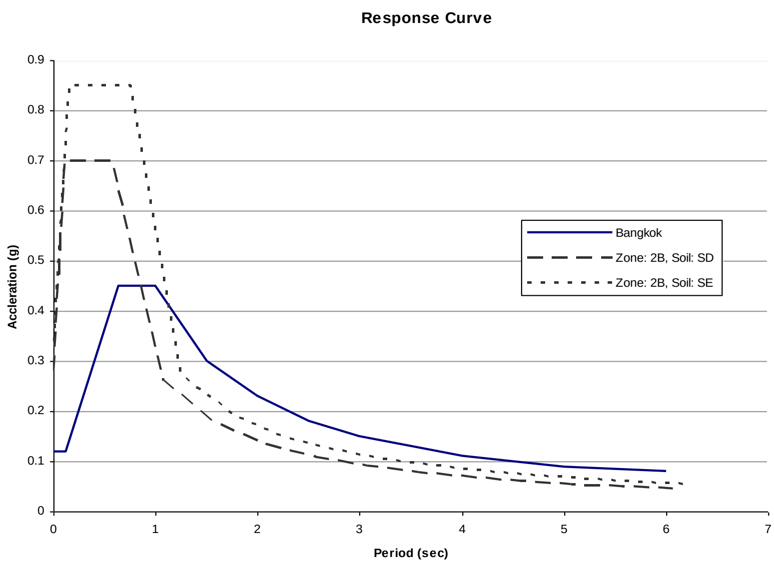


Figure 11 -- Response Spectrum Curve from UBC97 and Bangkok

4.5 Analysis Cases and Load Application

Complete linear static and nonlinear static analyses were carried out for different load cases, as summarized in the following table.

Table 3: Load Cases

Load Case Name	Load Case Type	Details
SW	Dead	Self weight of the structural component using self-weight multiplier in SAP 2000
FINISH	Dead	Finishing on slab (50 Kg/m^2)
LL	Live	15 Kg/m^2 at all slab panels
WX	Wind in X direction	50 Kg/m2 at wall panels
WY	Wind in Y direction	
EX	Earthquake in X direction	Using response spectrum curve for bangkok and from UBC 97

4.6 Capacity of Components

To evaluate seismic performance for this building, analysis results at every component and location are compared with capacity from laboratory test. Analysis results are calculated from many load combination based on UBC97 AND ACI318-2002.To find the structural component capacity, maximum loads for every laboratory test are converted to capacity unit(per meter) as shown in the following table.

Table 4: Analysis Results for Wall Panels

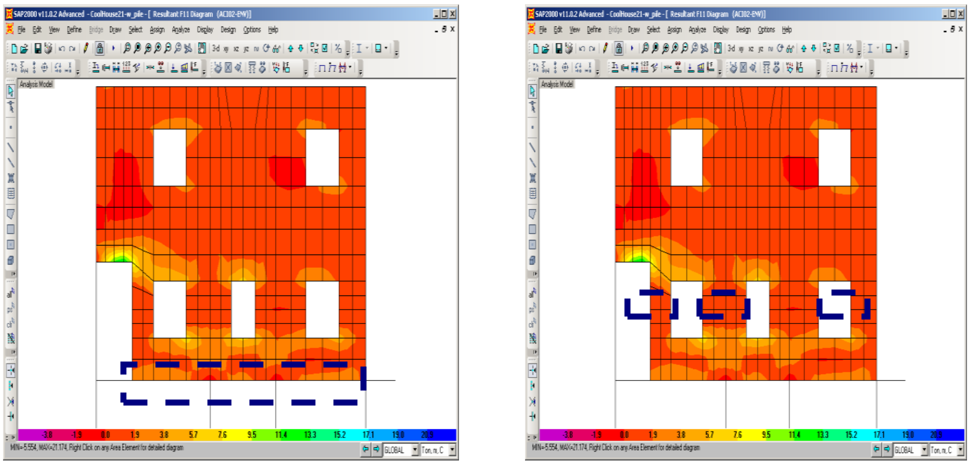
Component	Capacity	From Test	Width (m)	Results From Test	Capacity per Unit
Slab without Rebar	Bending Moment	Static Load Test No. 1	1.20	1.38 ton-m	1.15 ton-m/m
Slab with Rebar	Bending Moment	Static Load Test No. 2	1.20	2.45 ton-m	2.04 ton-m/m
Wall	Compression	Static Load Test No. 3	0.90	91.00 ton	101.00 ton/m
Wall	Tension	Cyclic Load Test No. 2	0.57	12.3 ton	21.58 ton/m
Wall	In-plane Shear	Cyclic Load Test No. 3	1.80	15.44 ton	8.58 ton/m

4.7 Analysis Results

Total forces (moment, in-plane shear, axial force) from analysis results in sandwich panels are been checked for global location. Each sandwich panel is divided in small panel to check local stresses especially at critical location.

Table 5-- Analysis Results for Wall Panels

Model	Foundation	Extra Wall	Earthquake Load	Level	Maximum In-plane Shear T/m	Maximum Compression T/m	Maximum Tension T/m
1	Pile System	No	Bangkok Response Spectrum	L1	5.25	16.21	2.56
				L2	2.17	9.20	4.54
2	Pile System	Yes	UBC97 Zone: 2B, Soil: SE	L1	6.32	27.41	10.76
				L2	3.68	20.12	11.18
3	Isolated Footing	Yes	UBC97 Zone: 2B, Soil: SD	L1	5.76	14.68	3.59
				L2	3.06	12.69	7.99



(a) (b)

Figure 12 – a) Sample of wall analysis results for global location: and b) Sample of wall analysis for local checks

4.8 Structural Performance Evaluation

For wall, slab and roof panels, demand capacity ratio (D/C ratio) is used to evaluate the structural capacity calculated by dividing the analysis results by capacity from test results. If D/C ratio is more than one that means the capacity of that component is not adequate. Capacity from test results, demand from analysis results and D/C ratio for each structural component are shown in the following tables.

Table 6-- Wall Panel Performance Evaluation (Maximum Values)

Model	Foundation	Extra Wall	Earthquake Load	Source	In-plane Shear T/m	Compression T/m	Tension T/m
Capacity From Test					8.58	101.00	21.58
1	Pile System	No	Bangkok Response Spectrum	Analysis Results	5.25	16.21	4.54
				D/C Ratio	0.61	0.16	0.21
2	Pile System	Yes	UBC97 Zone: 2B, Soil: SE	Analysis Results	6.32	27.41	11.18
				D/C Ratio	0.74	0.27	0.52
3	Isolated Footing	Yes	UBC97 Zone: 2B, Soil: SD	Analysis Results	5.76	14.68	7.99
				D/C Ratio	3.06	0.15	0.37

Table 7-- Slab and Roof Panel Performance Evaluation (Maximum Values)

Model	Foundation	Extra Wall	Earthquake Load	Source	Moment (ton-m/m) without Rebar	Moment (ton-m/m) with Rebar
From Test					1.15	2.04
1	Pile System	No	Bangkok Response Spectrum	Analysis Results	1.53	
				D/C Ratio	1.33	0.75
2	Pile System	Yes	UBC97 Zone: 2B, Soil: SE	Analysis Results	1.95	
				D/C Ratio	1.75	0.96
3	Isolated Footing	Yes	UBC97 Zone: 2B, Soil: SD	Analysis Results	1.25	
				D/C Ratio	1.09	0.61

5. Summary

The finite element models were been created to represent the sandwich panel system for a 2-story residential building based on architectural drawings from the client. Several load cases have been considered for these models including various seismic loads depending on soil and location of this representative building. Analysis results from these models at local and global location have been compared with capacity of each component obtained from laboratory tests to evaluate seismic performance of this representative building. Seismic performance for this representative building can be summarized as following.

For building in Bangkok on soft soil, this sandwich system for the representative building performs well under possible seismic load for Bangkok. Additional rebar are required in some locations at slab panels.

For building located outside Bangkok, whether on soft soil or stiff soil, extra walls are required in some location to distribute in-plane shear in sandwich panel system for the representative building. Additional rebar in same slab panels and wall were required.

6. Conclusion

From comparison between analysis results and laboratory test results, it is found that the sandwich panel system in this representative building performs well under UBC97 seismic zone 2B in which the demand is larger than the Thailand regulations (2A). This UBC97 seismic zone 2B is equivalent to earthquake 8.5 Richter scale at 70 kilometer from source, 7 Richter scale at 35 kilometer from source, 6 Richter scale at 20 kilometer from source and 5 Richter scale and 10 kilometer from source. Extra walls are required for the building outside Bangkok and additional rebar in slab panel are required for the building in some locations.

7. Acknowledgements

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