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Analysis of the Seismic Performance of SIPs

A White Paper

- Small scale panel test, University of California, Berkeley

Background Information and Intent

The goal of this report is to report on the use of Structural Insulated Panels (SIPs) in Seismic zones. The report looks to assist and give options to the SIP industry in regard to code acceptance for seismic construction. The report will:

1. review the current status of SIP industry's code issues;
2. Identify industry shortcomings regarding seismic testing, design, and approved use in seismic zones;
3. provide a resource on SIP's seismic response, highlighting testing conducted by the University of California Berkeley; and
4. propose future steps to increase SIP adoption in seismic construction.

We'd like to acknowledge the following partners for helping contribute to this report:

- Khalid Mosalem (UC Berkeley)
- David Tompos (NTA Inc.)
- Eric Tompos (NTA Inc.)
- Bill Wachtler (SIPA)
- Chris Schwinn (SIPA)
- BJ Yeh (APA)
- Mohammed Ettouney (Weidlinger Associates)
- Mike Mazor (DOW)
- Christian Meyer (Columbia University)

General Code Issues

The way SIPs are recognized by building codes is one of the most important issues currently facing the industry. While the applicable building code for a project is determined by the municipality providing the building permit, the majority of municipalities have adopted the I-Codes, a set of codes created by the International Code Council (ICC). The ICC has created distinct codes for One- and Two-story residential construction (IRC), larger commercial and industrial construction (IBC), energy conservation in buildings (IECC), and more. It should be noted that despite this baseline, however, that the local codes dictate the decisions and understanding of SIP performance.

Currently, the majority of SIP projects are residential construction under three stories. SIPs are recognized within the IRC through a prescriptive method in the *2007 Supplement to the 2006 International Residential Code* (IRC). This allows SIPs to be used without extra engineering measures. However, it also places limitations on the material composition of the panels, and their scope of use. To comply with the IRC prescriptive method, SIPs must be made with OSB facings and Expanded Polystyrene cores, and can only be used in wall applications in low seismic design categories (A through C) and for wind speeds under 130 miles per hour.

For SIPs used beyond the limitations indicated above, or for SIPs that are not manufactured in accordance with the prescriptive code requirements, the code acceptance is typically based on a code evaluation report issued by an evaluation or accreditation service. This is typically procured by a SIP manufacturer from the ICC Evaluation Service (ICC-ES), or by an International Accreditation Service (IAS) authorized Product Certification Agency (PCA). There are subtle yet significant differences between these two options, especially in regards to the development of seismic code approvals in the SIP industry, which will be explored later in this section.

Regardless of the approach to approval, products are evaluated in accordance with an acceptance criterion (AC). As of now, the evaluation of SIPs has been based on AC04, Acceptance Criteria for Sandwich Panels, and AC05, Acceptance Criteria for Sandwich Panel Adhesives. There are industry concerns that AC04 and AC05 are no longer adequate for SIPs with oriented strand board (OSB) facing materials, as both were developed for metal-facing sandwich panels. With that in mind, a new acceptance criteria, AC236, Acceptance Criteria for Structural Insulated Panels with Wood-based Sheathing Facers and Foam Plastic Cores, was drafted by ICC-ES in 2003. However, concerns about the testing required to comply with this criteria held it back from adoption, and industry concerns remain.

Unlike the IRC, there is no prescriptive method for the use of SIPs in the IBC. Under the International Building Code, SIPs are limited by the following relevant code areas:

- <u>Combustibility</u> based on ASTM E136 - 04 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C and ISO1182 Non-combustibility Test for Building Materials limit SIPs to…
    - In the IBC, Type V construction (three story max per Table 503) and have limitations stipulated by the building code in Chapter 6, Types of Construction and Chapter 5, General Building Heights and Areas; or
    - In the IBC, Exterior wall coverings in Type I buildings per 603.1.10.
- <u>Fire Rating</u> based on ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction allow SIPs to…
    - Show conformance to IBC 2603.4 Thermal Barrier. Note: each vendor must show compliance as a thermal barrier.
- <u>Weather Barrier</u> based on ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference allow SIPs to…
    - Show conformance to IBC 1403.2 as a weather barrier resistant to water intrusion and vapor permeability to allow drying while reducing vapor intrusion.
    - It should be noted that weather barriers are manufacturer/vendor specific. Typical details have been known to pass the weather barrier requirements, but each vendor must show compliance as a weather barrier.

Please note, that each manufacturer should supply data (through evaluation or certification reports) that their proper testing has been completed and verified demonstrating their system is compliant with the respective codes in the ICC.

Code Limitations Regarding Seismic Design

Code limitations regarding seismic design should be classified by building size. In the IRC, SIPs are limited to low seismic design categories (A through C) and for wind speed up to 130 miles per hour due to construction type classification. Seismic design in the IBC references ASCE 7—Minimum Design Loads for Buildings and Other Structures, excluding Chapter 14 and Appendix 11A. This document, developed by the American Society of Civil Engineers, dictates the determination of earthquake loads for buildings within the scope of the IBC and does not directly address SIPs.

The fact that SIPs are not directly addressed in ASCE 7 is a substantial issue for the industry, as neither AC04 nor the IRC/IBC addresses the requirements for high seismic design categories (D and E). Seismic applications have been a point of contention in discussions over developing new acceptance criteria for SIPs, and a source of complaint regarding AC04 and AC05. Current acceptance criteria do not address the requirements for high seismic design categories (D and E), such as in California, Oregon, Washington, and Alaska where SIPs are viable products. While the industry waits to develop and adopt new acceptance criteria (either AC236, or possibly AC130, *Acceptance Criteria for Prefabricated Wood Shear Panels*) all ICC-ES evaluation reports on SIPs will continue to not specifically recognize the use of SIPs in high seismic design categories. This imposes a considerable restriction to the market access of SIPs in West Coast.

The SIP industry is currently working towards achieving recognition in seismic codes by developing an ANSI standard with the APA, and by developing new acceptance criteria. However, there are two major steps required to overcoming this obstacle: identifying a testing method that is appropriate for the seismic evaluation of SIPs, and conducting further testing to better understand how SIPs function under seismic loading. (These issues are addressed in more detail in this report concluding in a roadmap for the industry as envisioned by SIPA's largest supporter, the APA.)

Professor Khalid Mosalam of the University of California in Berkeley is working to address the first problem. Current test methods are arbitrary, and have been adapted to the testing of wood frame or concrete construction, and they fail to recognize the full value of SIPs under seismic loading. His research, which is covered extensively in this document, validates the use of pseudo-dynamic analysis of panels. While this research is still not widely known in the engineering community, a successful program could change the methodology adopted in AC130 for evaluating SIPs for code compliance.

In addition to addressing measures of test methodology, more research is needed to systematically evaluate and enhance the performance attributes of SIPs. In the last few years, several SIP manufacturers have tested several full-size assemblies under test protocols designed to simulate seismic loading. Unfortunately, these tests were conducted with proprietary SIP systems and most data is not available to the public. Therefore, it is very difficult to develop generic design information for commodity SIPs systems even if the SIPs industry has a good faith in addressing the application of SIPs in high seismic design categories. In addition, Professor Memari of Penn State is working to further evaluate SIP panels, emphasizing the optimization of panel to panel connections. This research is still under way. It is referenced in this document, but because of its on-going nature, is not an emphasis of this report.

SIPA's Certification: Guide 65 Accredited

Guide 65 Product Certification Agencies (PCAs) are the alternative, accepted method to demonstrate code conformance within the industry for third party engineering, testing, and certification; however, SIPA PCA's (NTA Inc.) method is considerably different from ICC-ES with regard to what is done with the data. The ICC-ES method relies on direct use of test data, whereas NTA's method uses the data to develop engineering properties for the panel (this is described in the NTA Design Guide, attached as Attachment 1). The design guide procedures are currently undergoing peer review by APA. The Design Guide is limited to:

> "The design guide applies to structural insulated panels (SIPs), which shall be defined as a structural facing material with a foam core. This document does not apply to the design of reinforcement materials which may be incorporated into SIPs, such as dimensional lumber or cold-formed steel. All other materials shall be designed in accordance with the appropriate code adopted design standards. It is intended that this document be used in conjunction with competent engineering design, accurate fabrication, and adequate supervision of construction." (pg 1)

For example, ICC-ES's results are tabulated and cannot be deviated from, which ultimately hides the structural behavior of the panel. In contrast, the engineering properties developed by NTA's method permit analysis of SIP's under general loading and support conditions. This permits greater optimization of the panels during the design process. Furthermore, NTA's method explains the structural behavior by identifying and quantifying the possible limit states.

SIPA's certification and evaluation method produces more useful information with fewer tests, which lowers the expense and burden of bringing SIPs to market (particularly SIPs with new facings). It has been expressed that the cost of certification is a big barrier to wider SIP acceptance and use.

Regarding Seismic compliance, PCA's have the ability to write criteria for accepting SIPs in high seismic areas. SIPA currently has testing criteria applicable to OSB faced SIPs based on recommendations by the APA and relevant ICC-ES documents through their PCA. Additional details are provided in the commentary to NTA's Seismic Criteria (Attachment 2). Currently one SIPA manufacturer is qualified for SIP use in SDC D, E, F. The Seismic Criteria is limited to,

> “The purpose of a Technical Implementation Procedure (TIP) is to establish requirements for evaluating structural insulated panels (SIPs) faced with wood structural panels (labeled under DOC PS-1, DOC PS-2) in Seismic Design Categories D, E, and F of the International Building Code (IBC) and ASCE 7. This evaluation is based on confirming equivalent cyclic behavior between a conventionally constructed wood frame wall sheathed with wood-based structural panels mechanically fastened to wood framing members (ASCE 7 Table 12.2.-1 System A13) and a SIP wall assembly constructed to have the same nominal capacity. The performance requirements assure that the tested SIP details are equivalent to System A13 in ASCE 7 Table 12.2.-1 and permit the use of the seismic design coefficients, height limits, and detailing requirements for SIP lateral force resisting systems constructed based on the details from this evaluation” (pg 1)

Currently, only one jurisdiction has not accepted the PCA’s report permitting use in high seismic areas. Refusal of the report is based on limited resources within the jurisdiction to adequately review designs that include new building products. The lack of acceptance in one jurisdiction of the PCA’s certification is not evidence of a larger certification issue or concern, just a lack of a municipality’s resource and knowledge to quickly accept an outside certification (rather than ICC-ES’s evaluation report).

Evaluating SIP Panels Structurally

One of the most important aspects of SIPs gaining recognition in different building codes, especially in regards to seismic design, is proper testing to attain performance data. This section will describe how panels perform under seismic loading and the means of testing SIPs (pseudo-dynamic testing), and it will present the related testing data.

Understanding the seismic performance of SIPs requires an understanding of determining the earthquake loads that must be designed for as well as an understanding of how those forces will act on (and be resisted by) the panel and panel configuration.

Concentrated Loads

Core indentation is one potential result of concentrated loads. While much of the analysis for sandwich panels can be simplified through assumptions such as Saint-Venant's Principle that ignore concentrated loads, the impacts of fasteners and other points of contact should be accounted for. In addition to considering the effects of fasteners on sandwich panels, the design of fasteners themselves must be completed carefully. They must stand up to the required loads without failing.

Transverse Loads

A transverse load is a load applied perpendicularly to the plane of the longitudinal axis of a structure. How a panel deals with transverse loads is crucial for its performance in walls (dealing with wind loads), roofs (snow loads), or floors (the live and dead loads associated with occupancy).

Due to the relationship between transverse loads and shear stress, sandwich panels have advantageous characteristics for carrying these loads. In a similar fashion to the case of bending moments, the internal shear stress (τ) in a simply supported beam is inversely related to the moment of inertia:

$$\tau \equiv \frac{\mathrm{V} \cdot \mathrm{Q}}{I_A \cdot t}$$

In contrast to the case of normal stress due to bending moments (where faces experience the greatest stress), the core of the panel experiences the greatest shear stress due to transverse loads.

To measure the performance of SIPs in dealing with transverse loads, structural tests have been specified by ASTM International and the ICC in the standard building codes ratified by most municipalities.

The transverse load test measures deflection when a load is applied perpendicularly to the panel surface. For panels with brittle materials as facings, ICC requires "with a 5-pound-per-square-foot

(239Pa) horizontal loading imposed, the interior wall panel deflections shall not exceed" L/240, where "L" is the length of the panel.

The ASTM documents requires loads to be imposed in increments to failure, with deflections measured at each load. Deflection is monitored at "mid-span within 3 inches (76 mm) of each edge and at the center of the panel's width." ICC criteria for transverse load tests require "panels tested over a double span . . . to have the same three deflection readings taken at the expected maximum deflection point based on analysis."

Transverse load testing is conducted in accordance with Sections 4.2 and 4.3 of ASTM E72 standards, where a panel is placed horizontally on two steel beams that function as framing members. Two equal loads are applied by two hydraulic cylinders, each placed at a distance of one quarter of the span from the supports, toward the middle of the span. ICC requires "a preload of approximately 10% of the anticipated ultimate load to be applied to 'set' the panel in the test apparatus" and the deflection to be recorded. The panel is then loaded in increments to failure with deflection readings taken with each load at mid-span, within three inches of each edge, and at the center of the panel width. Deflection for the span is calculated by averaging the deflections obtained from each of the two micrometers.

Axial Loads

An axial load is a load applied along or parallel to and concentric with the primary axis of a structural member. The axis is typically in relation to a bearing wall or a column, and usually refers to vertical loads such as the weight of the building itself.

These loads result in normal stresses similar to those of bending moments. However, their distribution across the panel's cross-section does not have the same linear relationship. Using a combination of displacement and force equilibriums, the resultant normal stresses found in the face and core (constant throughout each) can be calculated as follows:

$$\sigma_c \equiv \frac{E_c \cdot P}{A_c \cdot E_c + A_f \cdot E_f}$$

$$\sigma_f \equiv \frac{E_f \cdot P}{A_f \cdot E_f + A_c \cdot E_c}$$

By calculating values using these formulae, the faces clearly experience higher levels of normal stress than the core. This stress level explains why the faces generally fail due to axial loads.

Per the IBC, axial loading must be accounted for if SIPs will be used in any structural use, including concentrated loads, eccentric, and side loads. Test procedures developed by ASTM and specified in local codes must be followed. Axial load tests are designed to determine a panel's capacity to carry vertical loads from roofs, floors, and walls and to resist lateral loads from wind forces. The ICC Acceptance Criteria for Sandwich Panels requires that: "load-bearing wall panels shall support an axial loading applied with an eccentricity of 1/6 the panel thickness to the interior or towards the weaker facing material of an interior panel." ICC determines the allowable axial load by dividing the ultimate load (a load that when applied will result in failure) by a factor of safety.

Allowed loads can also be established by finding the load at which the axial deformation is at or below 0.125 inches (if this load is lower than the load obtained by dividing the ultimate load by a factor of safety).

The test performed is a derivative of the test apparatus recommended by ASTM E72. A load is applied uniformly to the top of the panel, where two compressometers are placed two inches from each corner to read the axial compressive load. Deflectometers are positioned at mid-span to measure by how much the specimen deflects.

According to ICC, the allowable axial load is determined by dividing the ultimate load by a factor of safety. Factors of safety are explained above in Section 2.1.1 (usually a factor of 3.0 is used, since it incorporates all loading conditions).

Racking and Shear Loads

A racking load is a load applied in the plane of an assembly that lengthens one diagonal and shortens the other. A shear load is any applied external, translational load that creates shear stresses in a reacting structure. Per the IBC, if SIPs will be used in any structural use, including shear walls, racking and shear loading must be accounted for. Racking and shear loads must also be accounted for in seismic zones. The requirements depend upon the local building code as well as any regional supplements.

Racking shear tests are required for shear walls that resist wind and seismic loads. According to the ICC Acceptance Criteria, the allowable shear load is determined from the racking load at which a net horizontal deflection of ½ inch (12.7 mm) occurs, or by dividing the ultimate load by a factor of safety as listed under the ICC Acceptance Criteria for Axial Wall Tests.

ASTM E72 standards are designed to measure "the resistance of panels, having a standard wood frame, and sheathed with sheet materials such as structural insulating board, plywood, gypsum board, and so forth, to a racking load such as would be by winds." Performance of the sheathing is, therefore, defined as the test objective. According to ASTM standards, the test set-up calls for the specimen to be attached to a timber or a steel plate. This plate is then attached firmly to the base of a loading frame in such a way that will not let racking bear on the loading frame. A hold-down is also required to prevent the panel to rise as racking load is applied, and since "the amount of tension in the rods of the hold-down may have an effect on the results of the test, nuts on the hold-down rods shall be tightened prior to load application so that the total force in each rod does not exceed 90 N at the beginning of the test as determined by previous calibration. Loading is then applied through the timber that is bolted to the upper plates of the specimen. Lateral guides and deflection measuring devices are required. Deflectometers should be located in the lower left (to measure any rotation of the panel), lower right (to measure any slippage), and upper right corners (the total of the two plus the deformation of the panel) of the assembly. Load is then applied continuously" (ASTM E72).

The panels were tested using a variant of the ASTM standard with some exceptions: the timber load distribution member recommended by ASTM was eliminated and was replaced with "a steel sleeve to fit over a short block glued to the top plate" (ASTM E72) and the apparatus for measuring deformation was simplified. This method eliminated "the need for uplift, crushing and sliding gauges through the use of a light aluminum triangular frame resting on thin steel plates attached to the bottom plate" (ASTM E72).

Seismic Loads

The particle motion due to seismic forces is three dimensional, with x, y, and z components (x and y being considered horizontal, z being considered vertical). Building codes are mostly concerned with the horizontal components of ground motion and largely ignore the vertical component. Buildings are designed for vertical dead and live loads multiplied by a safety factor, and it is believed the safety factor will take care of any increase in stress caused by the vertical ground motion component.[1]

The first step towards seismic analysis and design is the determining of earthquake loads. This can be broken down into the following basic steps, each of which is outlined in ASCE 7:

a) Determining the maximum considered earthquake and design spectral response accelerations
b) Determining the seismic base shear in conjunction with the structure's dynamic characteristics (e.g., fundamental period)
c) Distribution of the seismic base shear within the building or structure.

Ground motion accelerations, represented by response spectra and coefficients derived from these spectra, shall be determined in accordance with:

- the general procedure described in ASCE 7 Section 9.4.12, and
- the site-specific procedure described in ASCE 7 Section 9.4.1.3.

Conditions on using these methods depend on the seismic use group and site characteristics of the structure. The procedure for determining the design spectral response requires determining the mapped *maximum considered earthquake spectral response accelerations* at short periods and at a one-second period, determining the *site class,* the *maximum considered earthquake spectral response accelerations (adjusted for site class effects*), and the design spectral response accelerations at short periods and a one-second period. Using these parameters, the general response spectrum can be determined in accordance with ASCE 7.

Each structure shall be assigned a seismic use group (ASCE 7 Table 9.1.3), based on its corresponding occupancy category (determined from ASCE 7 Table 1-1) and a corresponding occupancy importance factor as indicated in ASCE 7 Table 9.1.4 (and IBC Table 1604.5). All structures shall be assigned to a seismic design category based on their seismic use group and the design spectral response acceleration coefficients, S_{DS} and

[1] Chelapati, C.V. (ed.). Seismic Design Review Manuel, 3rd Ed. Pg 2-74.

S_{D1}, in accordance with ASCE Table 9.4.2.1a or 9.4.2.1b (or IBC Table 1616.3(1) or 1616.3(2)), whichever gives the most severe seismic design category.

The complex analysis procedures, which can be used within certain limitations, involve: index force analysis, simplified analysis, equivalent lateral force analysis, modal response spectrum analysis, linear response history analysis, and nonlinear response history analysis. These topics are outside the scope of this report.

The seismic base shear in a given direction is determined from the seismic response coefficient, determined in accordance with ASCE Section 9.5.5.2.1 and the total dead load and applicable portions of other loads as indicated in Section 9.5.3.

Once determined, the building design must be able to distribute these seismic forces within the building or the structure safely. How this is done is determined by the engineer and should be informed only by the design requirements and panels' design capacity values. This requires understanding how panels perform under seismic forces and how connections between panels are determined.

There is much disagreement within the SIP industry and in building codes as to how to evaluate this performance under seismic loading, and this is the key research question for this document. The following section will present the research and analysis conducted by UC Berkeley Professor Khalid Mosalam as one approach to this problem.

Evaluating Panels in Seismic Design (University of California at Berkeley Research)[2]

The performance of SIPs both mechanically and computationally during seismic and high wind events, is relatively unknown and unstudied. FAS and Professor Khalid Mosalam of the University of California Berkeley approached this industry shortcoming, asking the following questions: How do SIPs perform seismically? And what test method is valid to study a SIP's seismic performance?

Experiments are essential in evaluating the seismic and environmental worthiness of structural systems, including SIPs, and developing reliable computational tools. One approach is to subject a laboratory-constructed structure to earthquake motions using shaking tables. However, such tests are limited by the available capacities and high costs of shaking tables. On the other hand, in quasi-static testing, prescribed deformation or force histories are applied to the test specimen. This method provides valuable information on performance of various detailing alternatives for structural components [Leon and Deierlein 1996]. Unfortunately, it is not possible to strictly relate the energy dissipation in quasi-static tests to that required for seismic safety of structural systems. Some attempts [Nakajima 2000] with limited success and applicability have been made to use *fast quasi-static* tests to alleviate this problem.

[2] This section draws heavily from a draft proposal to NSF to fund research on Structural Insulated Panels for Seismic Construction submitted by Pacific Earthquake Engineering Research Center, UC Berkeley, the Structural Insulated Panel Association and FAS in 2007.

In general, the lateral load resistance of structures is mainly contributed by few critical components, e.g. shear-walls, which suffer the most severe inelastic deformations during strong earthquakes. Therefore, it may not be necessary to test the entire structural system and instead it is sufficient to only test critical substructures. There are several applications where testing substructures of a dynamically excited systems is preferred [Dermitzakis and Mahin 1985].

Overview of Research Plan

Over the research period, UC Berkeley tested a wide range of panels smaller than a full scale. These pilot tests using UC Berkeley's small-panel test machine had two primary objectives:

1) <u>finding the most appropriate assembly size and configuration</u> that gave a simulated seismic response that could permit rapid screening of the many variables impacting the seismic performance, and
2) <u>demonstrating pseudodynamic test methods and validating it</u> as a method for evaluating SIPs.

The initial test assembly configuration was based on wood SIPs which make up over 90% of the industry to identify the industry and practical considerations/inputs from the industry. After the analysis of the test results, it was recognized that despite the advantages of being able to test a number of replicates, thereby reducing the variation, there were some distinct issues including void and density distribution (as panels are reduced in size, the relative fraction of voids and areas of high and low density are obviously reduced proportionally).

The conventional approach to conduct simulated cyclic seismic test is to run monotonic test to obtain the load-deformation curve and from that curve obtain a reference deflection, $\Delta_r=0.6\Delta_m$ [Krawinkler et al. 2000]. From the maximum load, P_{max}, the deformation at $0.8P_{max}$ on the descending branch (deformation capacity, Δ_m) is obtained (deformation at P_{max}, i.e. Δ_{pmax}, can also be determined). **Both factors (0.6 and 0.8 above) are completely arbitrary, being largely based on seismic testing of other materials, e.g. reinforced concrete or steel. This justifies resorting to the more realistic pseudo-dynamic experimentation of the component tests.**

In future studies, attention must be given to the connections between panels forming a single shear wall capable of resisting seismic loading. In addition, conducting initial baseline testing of monolithically cast shear wall to evaluate the effect of introduced connections and improve the connection details is needed. It may be useful to consider areas of local density variations near connections (from X-ray images) to determine the density contribution and/or voids to panel behavior and their effect on sound connections between panels in a shear wall system.

Review of Structural Testing and Analysis of SIP/CSIP Panels

Most of the previously developed experimental or computational models lack the accuracy needed for a rigorous evaluation of SIPs. Furthermore, most models do not account for all types of degradation that are observed in the hysteretic response of these panels. Finally, no studies have attempted to model actual three-dimensional building structures subjected to combined effects of multi-directional shaking.

A halfway house between "true" dynamic testing using shaking tables and "practical" quasi-static approach is the pseudo-dynamic (*on-line*) testing [Aktan 1986] which is a primary focus of the UC Berkeley report. The potential of pseudo-dynamic testing is enormous [Mosalam 1996, Negro et al. 1996, and Seible et al. 1994a] especially if coupled with substructuring techniques [Demitzakis and Mahin 1985, Nakashima et al. 1990, and Nakashima and Masaoka 1999]. In this case, critical components, e.g. those expected to suffer severe inelastic deformations during strong ground motion, are physically modeled while the rest of the structural system is mathematically idealized in the control loop. A sequence of this approach is summarized as follows:

- Develop an approach for realistic optimization of the construction technique (i.e. connections) and material choice for SIPs (i.e. insulation, lamination, lamination reinforcement, and facings) by testing the available technologies as benchmarks and developing performance specifications to engineer and optimize panels to meet seismic, energy, durability, and strength specifications. There are three primary categories of performance specs:
    1. strength – how strong, how they respond to loading conditions;
    2. durability – how durable are the systems, do they break easily in handling;
    3. constructability – or ease of construction;
- Seismic and structural testing of basic physical components of a laminate, composite structural system that are developed as an outcome of the pervious step;
- Integration of physical modeling and computer simulation to study composite structural systems where benefits include utilizing computational advances and developing reliable models for the systems; and
- Final validation of the developed optimized, engineered (energy-efficient and seismically resistant) structural system and connections through shaking table experiment on a full-scale multi-story structural system.

Application of the pseudo-dynamic method has not yet been fully considered in composite construction as the one considered in this proposal. In composite construction, multiple connections exist requiring close monitoring of the performance for better understanding of the role of local responses on the global seismic performance. This close monitoring and need for realistic seismic loading make pseudo-dynamic testing a natural choice for composite structures. However, a general lack of connection performance knowledge hinders SIP seismic research, and this research need is a missing component in the SIP industry.

Overview of Pseudo-dynamic Testing

The pseudo-dynamic testing was first proposed in [Takanashi et al. 1975]. A US-Japan Cooperative Earthquake Research Program in the 1980's provided impetus for further development, with significant research effort in US occurring primarily at UC-Berkeley [Shing and Mahin 1983, 1984, 1985, 1987b and Shing et al. 1984] and University of Michigan, Ann Arbor [Hanson and McClamroch 1984 and McClamroch et al. 1981]. Comparative pseudo-dynamic and shaking table tests by Yamazaki et al. (1989) revealed concerns regarding loading rate effects and experimental errors. Takanashi and Nakashima (1987) and Mahin et al. (1989) summarize early development of the pseudo-dynamic testing in Japan and US, respectively.

Most of the first-generation pseudo-dynamic testing and research focused on the use of explicit time integration methods [Mahin and Shing 1985]. However, the application of explicit integration is limited by certain conditional stability limits and any experimental error added to the numerical process may develop rapidly into spurious higher mode response [Shing and Mahin 1987a, 1990]. The desire to test full-scale structures with many degrees of freedom and stiff shear-wall-type structures provoked research towards controlling higher-mode error propagation and introducing implicit integration to overcome the stability limit [Shing and Mahin 1987b, and Thewalt and Mahin 1987, 1995]. Recent developments have focused on pseudo-dynamic adaptations of implicit numerical integration algorithms. Two such schemes have emerged as the most widely accepted: i) the α-method [Shing et al. 1991a, 1991b] based on Hilber-α iteration [Hilber et al. 1976], and ii) the operator-splitting (OS) algorithm [Nakashima et al. 1990]. A summary of these second-generation pseudo-dynamic test methods can be found in [Shing et al. 1996]. Donea et al. (1996) present comparative results from pseudo-dynamic tests of three-story steel frame using implicit and central difference methods. Error analyses for implicit and explicit integration schemes can be found in [Peek and Yi 1990a, 1990b, Yi and Peek 1993 and Thewalt 1994].

Because of the above developments, use of pseudo-dynamic testing for stiff multistory specimens is becoming common. A major pseudo-dynamic testing program at UC-San Diego was conducted on a 5-story full-scale reinforced masonry structure. Two significant innovations evolved during this research, namely “soft-coupling” to improve actuator control and “generalized sequential displacement” to extend testing beyond a single ground motion [Seible et al. 1994a, 1994b, 1996]. In Europe, Donea et al. (1996) report on testing of a 4-story full-scale RC frame, and a reduced-scale series of bridge piers using substructuring. At Cornell University, pseudo-dynamic testing was conducted on a 2-story infilled steel frame [Mosalam 1996, and Mosalam et al. 1997, 1998] and infilled RC frame [Buonopane 1997]. Tests by Negro et al. (1996) used the central difference algorithm on a 4-story RC structure. Recently, tests conducted at nees@berkeley hybrid simulation system on RC frames with and without masonry infill walls and on timber shear walls [Elkhoraibi and Mosalam 2006], demonstrated the versatility of the system where mode switch between force and deformation controls and rate effects together with comparison with shaking table tests [Hashemi and Mosalam 2005] were performed.

Formulation of Pseudo-dynamic Methodology

Pseudo-dynamic test method is implemented by idealizing the structure as a discrete-parameter system. The structure is loaded, and displacements and restoring forces are *measured* during testing for use in subsequent calculations. The dynamic response of multi-degrees of freedom (DOF) system considering substructuring is governed by

$$M\ a_{i+1} + C\ v_{i+1} + K^C_{i+1}\ d_{i+1} + r^E_{i+1} = p_{i+1} \tag{1}$$

where M , C , and K^C_{i+1} are matrices of mass, damping, and computational substructure stiffness including interface DOF, respectively; a_{i+1}, v_{i+1}, r^E_{i+1} , and p_{i+1} are vectors of acceleration, velocity, restoring force of the physical substructure, and external force, respectively, at $(i+1)\Delta t$ with time step Δt , and d_{i+1} is the displacement of the computational substructure. Equations (1) can be solved using, e.g., an implicit-explicit Newmark β method [Hughes et al. 1979] (refer to equation (2)) where elements of the system are divided into: i) implicit (computational) group and ii) explicit (physical) group [Dermitzakis and Mahin 1985]. The terms of K^C_{i+1} corresponding to the DOF of the physical substructure and not at the interface between the physical and the computational substructures are zeros. Therefore, d_{i+1} on both sides of equations (2) is not a problem.

$$d_{i+1} = d^e_{i+1} + (\Delta t)^2 \beta\ M^{-1}\left\{p_{i+1} - C\ v_{i+1} - K^C_{i+1}\ d_{i+1} - r^E_{i+1}\right\} \tag{2}$$

where $d^e_{i+1} = d_i + \Delta t\ v_i + (\Delta t)^2\ (0.5-\beta)\ a_i$. Equation (2) can be rearranged as follows:

$$r^E_{i+1} = \left[(\Delta t)^2 \beta\right]^{-1} M\ \left\{d^e_{i+1} - d_{i+1}\right\} + p_{i+1} - C\ v_{i+1} - K^C_{i+1}\ d_{i+1}\,. \tag{3}$$

If the stiffness matrix of a large portion of the computational substructures remains elastic, efficient computation is achieved by *static condensation* [Clough and Wilson 1979]. The solution of equation (2) for a complex structural system with stiff components may suffer ill-conditioning. More importantly, for pseudo-dynamic testing of these stiff components, several problems are encountered [Thewalt and Mahin 1987, Seible et al. 1996]. *The use of mixed-variables with switching between force and displacement controls can be applied in the proposed project to alleviate these problems.* This can be achieved using equation (3) to convert some components of the calculated displacement vector into their corresponding force components leading to mixed-variables (forces and displacements) to be imposed on the physical substructure as follows:

- For stiff behavior under load control: apply r^E_{i+1} and measure corresponding displacement
- For flexible behavior under deformation control: apply displacement and measure corresponding r^E_{i+1}

In this way, flexibility to switch between load and displacement controls for different loading levels of the substructure is possible. The governing factor for this switch is the corresponding change of displacement, velocity and/or force such that this change remains within a desired range [Elkhoraibi and

Mosalam 2006]. The capabilities of nees@berkeley of mode-switch between force and deformation is capable of this performance. The challenge in this testing approach is to accurately perform mode-switching to capture the stiffening response expected after applied deformation overcomes slip between elements forming the shear-walls made of SIPs; *an issue that is expected to highly depend on the connections between the panels*.

Review of UC Berkeley Results and Discussion

Note: For a complete report refer to Attachment 3, "Seismic Evaluation Of Structural Insulated Panels." The following is a concise synopsis from the original paper. Please refer to the full report for detailed work description and findings.

Test results are presented for monotonic and cyclic tests conducted. Specimen 1 was tested as a preliminary investigation of the cyclic behavior of SIPs. Before a full cyclic regime was applied, a number of smaller "calibration" motions were applied to ensure that the instrumentation and data acquisition system were operating properly. Using information from Specimen 1, the testing of Specimen 2 represents a more refined approach, incorporating the procedures outlined in the CUREE protocol (Krawinkler et al., 2000). From this monotonic data, the reference displacement of 3.0" was calculated. Building on the lessons learned from testing Specimen 2, the same deformation of 3.0" was used as a reference value for designing the cyclic protocol for Specimen 3. In this case, the specimen was not subjected to monotonic runs prior to the cyclic test in order to gain insight into the behavior of an unscathed specimen.

When evaluating the relative performance of specimens, it is useful to consider the effect of loading rate. Specimen 1 was loaded manually with loading rate varying between approximately in the range 1-3 in/sec within the cycles. The loading rate for Specimen 2 varied in the range 0.03-0.9 in/sec, but the specimen was loaded such that the time required to complete one full cycle was constant at 20 sec/cycle. In contrast, Specimen 3 experienced a constant loading rate of approximately 0.15 in/sec, with the time for completion of a full cycle varying in the range 4-125 sec/cycle. For both Specimens 2 and 3, the loading sequence was automated, in turn providing more regular intervals between cyclic series. The differences in performance of the three specimens can therefore be attributed to a combination of factors, primarily the loading rate, number of cycles, and the presence of initial damage to the specimen due to initial monotonic loading.

In order to change the behavior from a rigid-body rotation to a racking motion, the use of tie-down anchors has proven successful (Jamison, 1997). From the tests performed by Jamison (1997), it was also found that the addition of a second base plate is ineffective in moving the failure mechanism away from the base connection. Schmidt et al. (1994) determined that uplift should be prevented by use of proper anchorage via anchor bolts, as uplift largely contributes to lateral wall displacement. Significant uplift was observed throughout the cyclic tests for all specimens, and should be minimized in future tests. Failures of all specimens occurred simultaneously along the bottom and top plates of the wall at the connections. Once a number of nails had failed, the wall appeared to rock under rigid body rotation about the center line of the wall.

When drywall screws were used in Specimen 1, it was observed that they failed in a highly brittle manner. The nailed connections in Specimens 2 and 3 were slightly more resilient, and could be re-hammered in order to regain some of their function after they started to fail via pull-out. In general, failure was best characterized by OSB splitting at the connection points, nail pull-through or pull-out, and foam crushing. With the connections broken, the rigidly rotating wall crushes the foam at either end of the panel. These observations are what would be expected, as experimental tests by Cheung et al. (1988) highlighted the sheathing-to-framing connection as the point of failure, while Stewart et al. (1988) described nail failures, including fracturing of the sheathing nail heads and withdrawal of nail shanks from the framing.

Specimens 4 and 5 were tested pseudo-dynamically using the procedures discussed previously and utilizing known ground motions levels. After levels I and II of earthquake loading, nails were re-hammered to bring capacities back to its original values before application of level III earthquake. Both specimens were tested identically for the repeatability of the results, which is confirmed from the comparisons. Level I (corresponding to 25% UBE) corresponded to almost elastic response with some energy dissipation through hysteresis and slight pinching response caused by the fasteners (nails) deformation. Increasing earthquake level to 100% DBE (level II) results in larger energy dissipation and pronounced pinching response. Finally, level III (100% UBE) corresponded to loss of shear strength where the load-displacement relationship in positive excursions experienced softening during the strong motion interval.

The UC Berkeley research show that the test results for material characterization of SIPs and CSIPs. However, racking test results of SIPs using quasi-static and pseudo-dynamic techniques represented the main part of the paper. The results confirmed the validity of pseudo-dynamic testing to characterize the SIPs seismic performance with less sensitivity to test parameters than quasi-static testing. Preliminary conclusions include reasonable energy dissipation and ultimate displacement ductility of 4.16 for SIPs without panel-to-panel connections. SIP strength was maintained up to and including 100% of the design basis earthquake (DBE) – 10%

The performance of a panel assembly under seismic forces is largely a function of its panel connections. However, the optimization of connections for seismic response is a significant unknown within the SIP industry, as no testing or testing protocol has been conducted. For the performance benefits of SIPs to be recognized, this testing must be conducted and panel connections must be optimized for seismic performance.

Furthermore, he stresses the following concerns and further research opportunities:

- “A thorough investigation of the development of common connection types would be beneficial, as this is the most likely point of failure in SIPs and SIPs. Both panel-to-panel and panel-to-diaphragm connections should be considered. Of special importance is the function of the adhesive within the connections, and whether its use represents any improvements of the performance." – This concern has been expressed in the Industry and is being researched by Penn State University.

- "Developing coupled computational tools for SIPs and SIPs to account for both thermal and structural behavior can advance applicability of this research beyond the realm of structural engineering treating the design of SIPs and SIPs in the context of optimization problems."
- "From sustainability point of view and due to increased environmental awareness, lifecycle analysis and assessment of SIPs and SIPs is an important task."

Evaluating Panel Connections and Connection Design (Penn State Research)

Since late 2007, Professor Ali M. Memari of Penn State has been working with SIP to address connections and attempt to level the knowledge between connection performance and manufacture. He stresses,

> "Aside from code, acceptance and qualification matters, there are some issues that SIP design professionals have identified through their experiences in SIP projects. These issues include lack of knowledge/experimental data about relative seismic performance of SIP panels that are connected using different types of splines, erected using different fastener types, and possibly anchored with or without hold-down devices.
>
> Up to this point, there has been few proprietary testing performed. However, the SIP industry has not developed many published reports that can be available to the public, especially in terms of the performance of SIPs under high wind and seismic loading. In particular, there is a need for better understanding of the load capacity of varying spline types and the connection hardware used to hold the panels together. The joint between two SIP panels is a critical aspect of the design and has to be able to resist large amounts of vertical shear…
>
> There is currently no publicly available testing report on the relative performance of varying fasteners used with different spline types under seismic loading. Some designers believe that nails work best in SIP construction, and that there are some fasteners that do not provide the integrity needed under certain loading conditions. Research is needed to compare various options and provide the public with experimental testing evidence on the attributes of different options" (pg 4, "Research Proposal Submitted to Structural Insulated Panel Association (SIPA): Cyclic Racking Performance Of Structural Insulated Panel Systems," Principal Investigator: Ali M. Memari, Ph.D., P.E., Associate Professor, Penn State University; December 27, 2007).

Although a final report is pending, Professor Ali M. Memari's reports should achieve the following…

> "The primary objective of this proposed study is to characterize the cyclic racking response of a selected number of SIP wall configurations. The procedure for full-scale inplane racking testing will follow that prescribed by ICC-ES AC130 using CUREE loading protocol. The test results will be developed such that the SIP wall systems can be evaluated based on both ICC-ES AC130 and ICC-

ES AC04 Appendix A (2005). The results will also provide a basis for comparison of the effect of parameters that will be varied in the tests, including two spline types and three fastener types." (pg 5, "Research Proposal Submitted to Structural Insulated Panel Association (SIPA): Cyclic Racking Performance Of Structural Insulated Panel Systems," Principal Investigator: Ali M. Memari, Ph.D., P.E., Associate Professor, Penn State University; December 27, 2007).

Professor Ali M. Memari and Professor Khalid Mosalam's work is complementary and both hope to expand SIPA's options in meeting existing and future code and certification needs in the industry. One area of particular interest for future research funding is combining these important seismic research studies to compile a unified analysis regarding composite panel engineering mechanics of composite panels.

Industry’s Seismic Roadmap

While, the SIP industry as a whole is collectively moving industry-wide to common standards and metrics (through a Guide 65 Product Certification Agency (PCA) as recommended to the industry by FAS in the report, “Product Certification and Evaluation: A Comparison of Approaches to Building Product Approval”), the ultimate goal is general structural certification of SIPs. This certification for use in seismic zones is the limiting factor to larger scale SIP adoption.

Panel Type vs. Seismic Robustness

At the beginning of this research without any panel performance data, FAS proposed that panel type, and more specifically insulating core type, would dictate seismic performance or robustness. However, Professor Mosalam’s research and the research conducted by Penn State suggest that panel core type is not as important as panel connection type and details, which more significantly affect the thermal performance of the structure. Therefore, FAS developed a design guide to optimize the thermal performance for these connections. However, FAS has not integrated the seismic research because the panel connection research completed by Penn State is incomplete. More research is needed to justify panel connection type and its seismic response factor then the panel connection types can be classified by thermal efficiency.

Therefore, the matrix of panel type and seismic use can be developed in short hand as follows:

I. Consideration of Permissible Code Use:

Core Type	**Seismic Use**
EPS 4.0 R per inch	Dependent on product code approval, see notes below
POLYURETHANE 6.7 R per inch	Dependent on product code approval, see notes below
XPS 5.4 R per inch	Dependent on product code approval, see notes below

Per section 1708 of the IBC, the registered design professional is responsible for stating the applicable seismic qualification requirements for designated seismic systems. Each system component shall be tested by the manufacturer, with certification and results reviewed by the building official. This testing shall be by an actual test on a shake table, three-dimensional shock tests, an analytical method using dynamic characteristics and forces, the use of experience data, or a more rigorous analysis providing for equivalent safety. Ultimately, the seismic response is governed by code acceptance from the panel manufacturer as a certified assembled product. Therefore, code approval and certification are more important considerations than core type for architects, engineers, and builders.

II. Consideration of Connection Type:

Furthermore, optimization of a system's connections will more substantially impact thermal performance and energy efficiency than an architect, engineer, or builder switching systems outright. Any design guide should instruct an architect, engineer, or builder on how to determine the baseline panel thickness, provides a general procedure to optimizing the connections of the system (thermally), and provides a method on how to estimate the wall's thermal efficiency. Finally, the design guide should present a general design procedure to correctly address whole building energy efficiency and tightness.

Roadmap for Seismic Acceptance

Ultimately, the number one roadblock for SIPs in seismic construction is code certification. In general, code certification is somewhat complex given that SIPs are assembled products. The APA summarized these issues in a letter to the industry (presented below). The APA provided the industry with a candid and concise status of code approval and certification as well as the troubles in gaining full seismic code acceptance:

> **APA status: Issues Associated with the Code Acceptance of SIPs**
>
> "Prescriptive SIPs have been adopted by the *2007 Supplement to the 2006 International Residential Code* (IRC). These prescriptive SIPs are limited to wall applications. In addition, by default, the IRC is limited to low seismic design categories (A through C) and for wind speed up to 130 miles per hour.
>
> For SIPs used beyond the limitations indicated above or if SIPs are not manufactured in accordance with the prescriptive code requirements, the code acceptance is typically based on a code evaluation report issued by the ICC Evaluation Service (ICC-ES) to the SIP manufacturer. ICC-ES conducts product evaluation in accordance with an acceptance criteria (AC) approved by the ICC-ES Evaluation Committee composed of selected building officials around the country. As of today, proprietary SIPs have been evaluated based on AC04, *Acceptance Criteria for Sandwich Panels*, and AC05, *Acceptance Criteria for Sandwich Panel Adhesives*. In recent years, however, ICC-ES has expressed concerns that AC04 and AC05, which were originally developed for metal-facing sandwich panels, are no longer adequate for SIPs with oriented strand board (OSB) facing materials.
>
> Therefore, a new acceptance criteria, AC236, *Acceptance Criteria for Structural Insulated Panels with Wood-based Sheathing Facers and Foam Plastic Cores*, was drafted by ICC-ES in 2003, but failed to be adopted by the ICC-ES Evaluation Committee due to the lack of support from the SIP industry. It is generally considered by the SIP industry that the draft AC236 is too onerous and will require a significant amount of new testing for compliance with the new criteria.
>
> One substantial issue with AC04 and AC05 is that it does not address the requirements for high seismic design categories (D and E), such as in California, Oregon, Washington, and Alaska where

SIPs are viable products. There is a new AC130, *Acceptance Criteria for Prefabricated Wood Shear Panels*, which can be used to develop design information for high seismic design categories. However, ICC-ES has been reluctant to adopt the AC130 methodology partly because of the pending AC236 development. Therefore, up to point in time, all ICC-ES evaluation reports on SIPs have not specifically recognized the use of SIPs in high seismic design categories. This really imposes a considerable restriction to the market access of SIPs in West Coast.

In the last few years, several SIP manufacturers have tested quite a few full-size assemblies under test protocols designed to simulate seismic loading. Unfortunately, these tests were conducted with proprietary SIP systems and most data are not available to the public. Therefore, it is very difficult to develop generic design information for commodity SIPs systems even if the SIPs industry has a good faith in addressing the application of SIPs in high seismic design categories. It is generally recognized by the SIP industry that a concerted effort is required to develop generic information before SIPs can be widely used in construction. An American National Standard for SIPs that is under development by APA – The Engineered Wood Association in working with the Structural Insulated Panel Association (SIPA) will serve as the consensus product standard for SIPs. Obviously, more research is needed to systematically evaluate and enhance the performance attributes of SIPs. A research project underway at the Penn State by Professor Memari is headed toward this direction.

An area of research that could be beneficial to SIP industry is the use of pseudo-dynamic analysis to study the system performance of SIPs under seismic loading. This has been carried out by Professor Khalid Mosalam of the University of California in Berkeley. While this research is still not widely known in the engineering community, a successful program could change the methodology adopted in AC130 for evaluating the SIPs for code compliance. This is especially important when the SIP industry reactivates the development of AC236 in 2008." Borjen ("BJ") Yeh, Ph.D., P.E., *Director, Technical Services Division,* APA

As a result of this letter, the industry is approaching seismic acceptance in two primary veins:

1. continued research on an alternative testing standard (through UC Berkeley, but now privately funded by SIP companies[3]) for future acceptance by the ICC-ES as a valid test method and, ultimately, blanket acceptance by all municipalities, and
2. development of a testing method by SIPA's PCA to get full Seismic certification by each municipality.

[3] The industry hopes to support UC Berkeley for further testing as an independent source specifically for research regarding higher ratio tests larger than 1:1. This data will allow the industry to present the independent data when there is resistance to code approvals and acceptance due to the current ICC ESR 1882 testing limitations or, separately, individual municipality concerns. Separately, UC Berkeley should seek funding to develop the engineering mechanics of SIP panels for seismic applications and a full scale 3d SIP test.

Further Research Needs

This research project has identified several outstanding issues and qualifications that the industry needs to address. These include:

1. Further research is needed to develop the engineering mechanics of panels specific to seismic events.
2. The definition of a SIP is vast a various. There is not a industry specific definition of SIPs, therefore, all sandwich panels fall within this general category no matter if they are laminated, reinforced, or hybrids of traditional systems (i.e. including intermediate supports). The testing standards should recognize and address this deficiency and stipulate composites that fall within the definition of a SIP. These testing standards should also address limitations and reinforcements.
3. Connections throughout the industry have been driven by constructability issues and not engineering analysis and optimization. Sufficient research needs to be directed into the research of new connection systems, evaluation of connections, and general accepted connection standards. Connections will be the limiting factor of shear and combined loading which may benefit the structural performance of buildings.
4. Diaphragms assemblies need more thorough testing in the industry. Combined shear and tension acting on the panels is assumed to be carried at the connection. The testing standards should include some acknowledgement of diaphragm testing procedures and creep.
5. The industry needs standards for manufacturing, testing, material handling (including maintaining the chain of custody and compliance) and industry accepted quality assurance and control.
6. Non-proprietary seismic test data applicable to all SIPs. Note, the Penn State research may fulfill this need when complete.
7. More thorough creep testing program than what is currently in the literature. SIPA's design method exposes that fact that the current creep data is most likely conservative and requires further investigation to truly provide optimized SIP panel design under long-term loads.
8. Testing program to assess the use of SIPs to resist tensile forces (this would primarily be an assessment of possible spline connections). Currently, some extreme measures are taken to make SIPs work in Florida and Gulf Coast because no method or values exist for SIPs to carry tensile forces. We know they can do this. We just need to test the top/bottom top connection details to ensure proper performance.
9. Although not considered in this report, openings and penetrations are not properly addressed within the analysis of SIPs. The testing standards should address penetrations in the wall by setting ranges of unsupported penetration spans.
10. Although not considered in this report, the testing program to assess and develop design methods for unreinforced holes/headers in wall panels. Much of industry practice is based on rules-of-thumb, if the design community can't understand it they won't embrace it.
11. Although not considered in this report, fire resistance needs more education within in the industry. SIPs may be fire rated, but they are not non-combustible. The fire resistance of a polystyrene core is

always going to be the limiting factor, thus new insulations must be deployed if SIPs are to ever be considered for uses in bearing wall construction of multistory buildings. The SIP industry needs more education of architects and engineers on the fire resistance aspects of the products for them to be accepted for non-residential uses.

12. Although not considered in this report, knowledge of adhesives and long term durability must be evaluated against the durability of the subsequent constituent materials. Are the adhesives perfectly rigid like the facing materials to only be attached to a flexible core, or are the adhesives flexible? Is the durability of the system limited to the lowest durability of the constituent materials?

REFERENCED ATTACHMENTS

ATTACHMENT 1: NTA Design Guide for SIPs

ATTACHMENT 2: NTA Seismic Criteria

ATTACHMENT 3: UC Berkeley Report Entitled, “SEISMIC EVALUATION OF STRUCTURAL INSULATED PANELS,” Khalid M. Mosalam, Joseph Hagerman and Henry Kelly