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I-SSB: The Integrated Safe & Smart Built Concept

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ABSTRACT: The paper presents selected results of the INTEGRATED SAFE & SMART BUILT CONCEPT (I-SSB) Integrated Project, financed by the European Commission in Framework Programme 6 in the frame of the NMP theme (Nano-technologies and nano-sciences, knowledge-based multifunctional Materials and new Production processes and devices). The project has developed an "Intelligent house" concept that combines comfort with hazard resistance by integrating modern design and construction methods with novel components, sensors/actuators and monitoring systems collaborating with the structure. In particular, earthquake - vibration - noise and fire-safe solutions have been developed and demonstrated in drywall, steel-frame construction accounting for long-term seismic and fire safety.

The overall concept of the I-SSB project, as well as particular developments in building components and sensors are presented. New types of plasterboards with improved ability to withstand the extreme conditions occurring during earthquake or fire have been developed and successfully tested. Developments in sonic attenuation, vibration absorption and indoor parameter monitoring systems are highlighted. The results of the seismic tests performed in a "mock-up" structure based on the I-SSB concept and a full-scale residential house designed to sustain extreme loads of wind, vibrations and earthquake and constructed in Greece are presented. Both have been equipped with innovative sensors/actuators to reduce man-induced vibrations, control noise and seismic activity.

1 INTRODUCTION

The construction sector is central to the overall economy of the European Union, accounting for more than 10 % of GDP, employing more than 16 million people, providing accommodation and infrastructure, and playing a prominent role in the global marketplace. It is a major source of revenue from exports and an evident contributor to the quality of life for all citizens. Climatic change, growing safety consciousness and increasing quality-of-life expectations impose growing demands on the designers and builders of dwellings.

To meet these requirements, the INTEGRATED SAFE & SMART BUILT CONCEPT (I-SSB) Integrated Project, selected for financing by the European Commission in Framework Programme 6 in the frame of the NMP theme (Nano-technologies and nano-sciences, knowledge-based multifunctional Materials and new Production processes and devices) has developed an 'Intelligent house' concept that combines comfort with hazard resistance. The I-SSB Project started in January 2007 and during its 4 years duration developed an earthquake -

vibration - noise - fire safe concept based on multi-functional load-bearing drywalls coupled with dynamically optimized steel skeletons to account for long-term seismic and fire safety through collaboration of the structure with components and monitoring systems.

The consortium of the project comprised 22 partners from 11 EU countries and covered all complementary disciplines required for the development of the I-SSB concept with expertise in the areas of construction, drywall systems, anti-seismic design, structural dynamics, risk assessment, nanomaterials, advanced multi-functional, composite, structural strengthening, vibration damping and fire-retardant materials, sensors, seismic and fire experiments, fire and structural modeling, information technology, and environmental assessment. The project has been coordinated by Prof Dr. Hans-Ulrich Hummel, Knauf Gips KG with the support of Prof. Maria Founti, National Technical University of Athens on technical and scientific matters and Dr. Alexander Lucumi, KIT, Germany on administrative matters. The total cost of the project was €9853200, out of which €6000000 was contributed by the European Commission. More information about the project and links to the sites of the contributing partners can be found at: http://www.issb-project.com/

One of the outcomes of the Project was the development of training material in the form of a book titled “Seismic Design and Drywalling” authored by Fritz – Otto Henkel (Wölfel Beratende Ingenieure GmbH + Co. KG), Dennis Holl and Manfred Schalk (Knauf Gips KG) which has been translated in several languages (e.g. Giurdas).

1.1 The I-SSB concept

The I-SSB concept couples modern construction practices (lightweight steel frame with drywall systems modular buildings) with sensors, information technologies and advanced materials to develop a new type of noise, vibration, earthquake and fire safe building.

Modular buildings using heavy steel skeletons and/or lightweight frame/studs can be constructed very quickly, are flexible, economical, with good standards of heat insulation and comply with the same building regulations that apply to all construction – brick, steel or concrete. Gypsum plasterboards are widely used in drywall construction as an aesthetically pleasing, easily worked but mechanically enduring facing material. They are commonly used as passive building elements, as infill wall-, ceiling- or flooring elements with low shear stress properties connected to a sub-construction based on metal studs of various geometries. They are easy to apply and exhibit good mechanical and thermal properties. The combination of steel skeleton with drywall systems offers additional load-bearing capability, increased partition heights, wider floor spans, better fire resistance, improved sound resistance and higher thermal insulation. In the context of building fire safety, gypsum plasterboards are capable of slowing the penetration of fire through walls and floors, due to the endothermic gypsum dehydration process that takes place in high temperatures [Sultan (1996), Manzello et al. (2007)a and b]. The mounting and fixing of such elements is state of the art. This combination of proven manufacturing techniques makes them ideal for the “I-SSB” concept.

Although the probability of a major earthquake in most EU regions, except the entire Mediterranean and Balkan area, is low, current building codes (e.g. Eurocode 8) require earthquake resistant design in moderate- (or even low) seismic regions. An earthquake may initiate fire in the damaged buildings. Current experience of anti-seismic design with drywall systems is limited to non-load bearing elements, which have to be isolated in case of severe vibration-resonance. Such elements do not take up abrupt changes in load distribution and therefore cannot sustain severe deformations. The horizontal deformation caused by the earthquake and the subsequent cyclic load may bring about degradation of steel structured frames. Current practices do not account for active control of important structure parameters especially in cases of severe damages. Structural frames are not optimised for extreme loads (e.g. under seismic or fire conditions) and are not coupled to other load-bearing elements. Furthermore, no building materials/structural components exist at commercial level that can react and re-adjust their performance to suspend the external excitation.

The above problems cannot be solved with conventional technology. New scientific knowledge and radically new technologies are necessary in order to efficiently address the material inefficiencies and the technical limitations. A new building scheme has to be developed, capable of fulfilling residential needs of everyday comfort (man induced noise control, traffic, acoustic noise, indoor condition regulation), of occasional sporadic security (flood, fire) and the once in a life-time need of extreme safety in adverse conditions (earthquake).

The current paper presents only part of the scientific achievements of the I-SSB project. It concentrates on developments relating to improvements in the earthquake and vibration performance of gypsum plasterboards, the development of active and semi-active sensors for control of noise, vibrations and earthquake and the demonstration of the anti-seismic behavior of the above in a so-called "mock up" construction designed using the new structural dynamic approaches and materials. The results are demonstrated in a full-scale residential building constructed on the basis of the new concept, named the I-SSB house. Results relating to the development of new materials (e.g. fire retardants, photo-catalytic, self-repair), to static-dynamic cycling testing and to fire performance of components and assemblies, to the development of novel computational tools for dynamic modeling of lightweight structures and mico-meso-macro scale modeling of fire performance of gypsum, gypsum based building components and of the entire I-SSB house as well as the wireless network installed in the I-SSB house for remote monitoring and assessment of performance of the sensors, are not presented here for reasons of space.

2 NEW PLASTERBOARDS AND MATERIALS

The main advantages of drywall non-load bearing partitions are the reduction of construction weight (Table 1) and the ductile behavior of deformation. The dead load decrease of non-load bearing construction components leads to a massive reduction of loads in the event of an earthquake. This makes drywall partitions ideal for use as infill walls for skeleton constructions. The brittle and comparatively rigid deformation behavioral patterns of infill masonry generally causes load transfer with dangerous, brittle and unannounced collapse that can even lead to the total collapse of the building. Even when highly deformed, drywall partitions maintain their enclosing function and do not collapse completely (Tschirgin/Tscherkaschin, 2004).

Table 1 Weight comparisons of infill masonry and drywall systems

Partition characteristics	**Weight per unit area**
Infill masonry d =11.5 cm	approx. 145 kg/m ²
Metal stud partition, single layer	approx. 25 kg/m ²
Metal stud partition, double layer	approx. 50 kg/m ²
Weight reduction	65 % to 83 %

2.1 Superplasticizer (Sika Technology AG)

Considerable advancements have been achieved in the frame of the I-SSB project in materials and products used in sealing, bonding, damping, reinforcing and protecting load-bearing structures in construction. One focus was the development of new superplasticizers with the use of polycarboxylate (PCE) dispersants as additive for plasterboard manufacturing with ultra-high resistance to vibrations and earthquake tremors, which enables a faster and more economical gypsum production. It is desirable to reduce the amount of water used in gypsum board production lines to save energy and production cost associated with water removing.

Sika Technology AG used own know-how of concrete superplasticizer technology to formulate PCE based plasticizers for gypsum. PCE based dispersants provide fluidity to gypsum slurries at reduced water content. Compared to melamine and naphthalene condensates, which are nowadays typically used as plasticizer in wall board production, PCE based plasticizers are free of formaldehyde and therefore environmentally and ecologically unproblematic.

In the frame of the I-SSB project around 150 PCE based polymers were synthesized in lab scale. The performance of the polymers was tested in slurries of gypsum, water and plasticizer with and without accelerator. The flow and the setting time were determined. Sika selected among these and produced polymer “GPV 12” in plant scale. It was demonstrated that with the new PCE based superplasticizer “GPV 12” a water reduction up to 20% is possible to get the same flow performance in gypsum as with the benchmark case. A reduction of retardation could be achieved by variation of polymer and/or accelerator dosage. The wallboard test production confirmed the potential of “GPV 12” as superplasticizer for plasterboards. In the tests a water reduction of 300-400 g per m^2 plasterboard was achieved.

2.2 Reinforcing system for gypsum wallboards - Dynamic and durability tests (SIKA Technology AG)

Another objective was the design of connection joints between the gypsum wallboard and the steel frame. The best performing adhesive has been specified in terms of bond strength, vibration absorption, and durability. Additionally a reinforcement system for the gypsum wallboard and the steel frame has been designed. Again the best performing adhesive has been specified in terms of bond strength, vibration absorption, and durability.

The final reinforcing system for gypsum wallboards is the Sika® glass fabrics type 270, bonded on both sides of the boards with two component epoxy Sikadur®-330. This showed the best properties for application and strength. For the reinforced GKF-wallboards the reached maximum force at dynamic load was approximately 20% lower, in relation to monotonic loading. This is still three times higher compared to boards without glass fabrics reinforcement.

2.3 Optimised and functionalised drywalls and ceiling tiles - Sound absorption boards (Knauf Gips KG)

Plasterboard can be functionalised by different methods. The board core can be equipped with special additives giving rise to special functions. Alternatively standard boards can be modified geometrically by bowing or by punching holes into surface. Perforated boards are frequently used in ceiling construction for sound absorption. Special mounting and fixing technology is needed for construction. By substitution of 40 % gypsum by 60 % $BaSO_4$ on standard board lines a special board was obtained which is heavy by weight but showing an internal flexibility giving rise to high sound reducing performance when used in wall constructions. Special screws are needed for this purpose and special metal under-construction gives rise to very high sound attenuation figures.

2.4 New floor elements (Knauf Gips KG)

Special floor constructions, called highrised floors, can be constructed using boards of gypsum-fibre-composition as final layer. The elements of standard dimension 600 x 600 mm are mounted on special supports and individual elements are connected to each other by tongue-groove technology. Special gypsum-fibre-boards were developed consisting of 90 % gypsum, $CaSO_4 \cdot 2 H_2O$ and 10 % of refined cellulose (waste paper ~ 80 %, virgin paper ~ 20 %). The boards for highrised floors showed a high strength and are currently available in dimensions 1200 x 600 mm or 600 x 600 mm. The height of highrised floors is controlled by special support and span is 600 mm but at edges 300 mm. Support carries two or three boards and the boards are mounted via tongue and groove, connected with some adhesive.

2.5 New load bearing drywall elements (Knauf Gips KG)

In general, drywall systems are "non-load bearing" by definition. However, non-load bearing drywall partitions show some load bearing capacity. A special plasterboard has been developed with high stability and high grammature of paper (heavy paper quality with grammature of 200g/m²). (Brand name: Diamant). The gypsum core of this board shows a high density - improved mechanical stability and stiffness and special screws are needed for fixing and mounting. By combination of Diamant and special screws the resulting walls show significantly higher rigidity and stiffness (Figure 1). As a result it has been possible to construct walls that can be increased in height by 30 %, compared to walls with standard components. In addition, methods and tools for mounting and fixing of modified plasterboard on steel construction have been developed and tested.

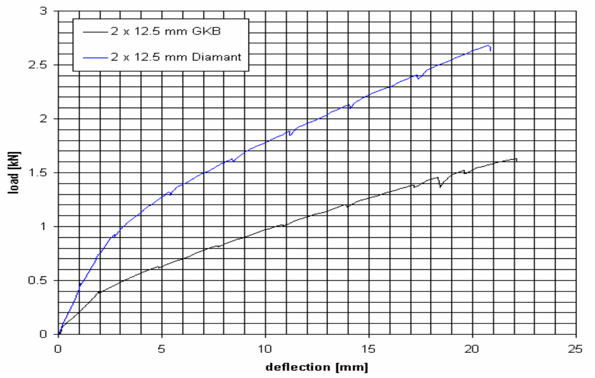

Figure 1. Bowing of "Diamant" boards compared to standard wall W 112 on CW 50 profiles (d=625 mm)

3 SENSORS - ACTUATORS

Lightweight buildings are sensitive to vibration excitations such as human behavior, traffic, external shocks and/or earthquakes. The sensitivity of lightweight buildings for this load case is caused mainly by their low mass and their low eigenfrequencies. If one or more eigenfrequencies lie in a frequency band which is excited e.g. due to movements of the occupants, resonance could occur. Human behavior and/or traffic may lead to both local vibrations - structure borne noise characterized by very small vibrations of parts of the structure - like floor vibrations and to noise problems. An earthquake or an external shock leads to global vibration forms of the entire building which could lead to damage or destruction of the building structure. Within the I-SSB project passive methods as well as semi-active and active methods to avoid or to combat the resulting vibrations were investigated.

A novel 3D-earthquake sensor based on high performance piezo-fibre modules has been developed and tested for active vibration reduction together with an active absorber to reduce human induced vibrations as well as a PZT-fibre based acoustic actuator (Figure 2). Piezoelectric materials and wafers were used as distributed sensors and actuators in smart structures and/or as active materials for controlling low energy structure vibrations. Thin wafers were glued on the surface of the base structure. No connection to the electricity network or use of batteries is necessary.

The PZT-fibre based sensors for the monitoring of man-induced vibrations and earthquake, and the PZT-fibre based actuators for the control of structure-borne noise developed by Wölfel Beratende Ingenieure GmbH & Co. KG and the Technical University of Darmstadt, Germany offer extremely high sensitivity, large bandwidth, allow for energy harvesting (autarkic), ability for self diagnosis and are ideal for light construction & large area applications.

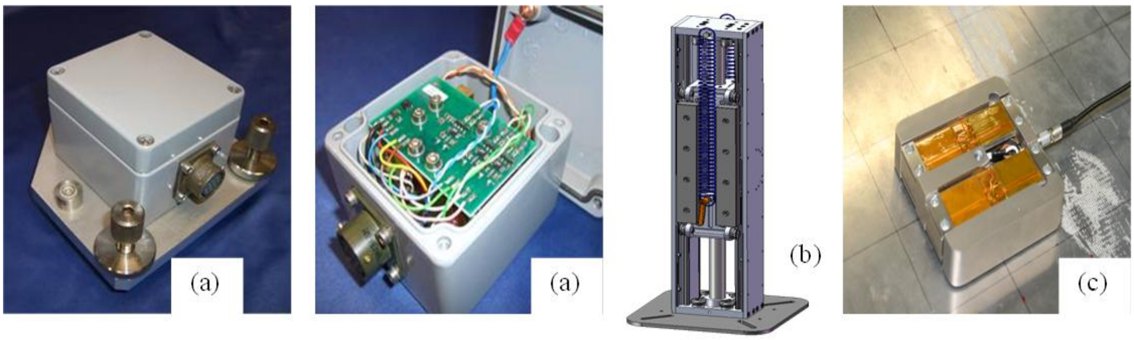

Figure 2. (a) New PZT fibre sensor; (b) Active absorber; (c) new concept of acoustical mass actuator

Magnetorheological (MR) fluids basically consist of small magnetically polarizable particles that are dispersed in a carrier liquid and stabilized by chemical additives. Applying a magnetic field can drastically change their rheological properties; this effect is fast (within some milliseconds) and reversible. A semi-active system, a novel MR damper (Figure 3) has been developed by Fraunhofer-Institut fuer Silicatforschung ISC, Germany to prevent damage to highly sensitive equipment during an earthquake. The MR damper consists of two separate assemblies protecting the control cabinet against horizontal and vertical vibrations. The components of the MR damper were designed according to the requirements of the load case earthquake. The MR-damper will protect an electrical control cabinet (Figure 3) placed inside the mock-up house and the demonstration house built within the I-SSB project to protect valuable instrumentation.

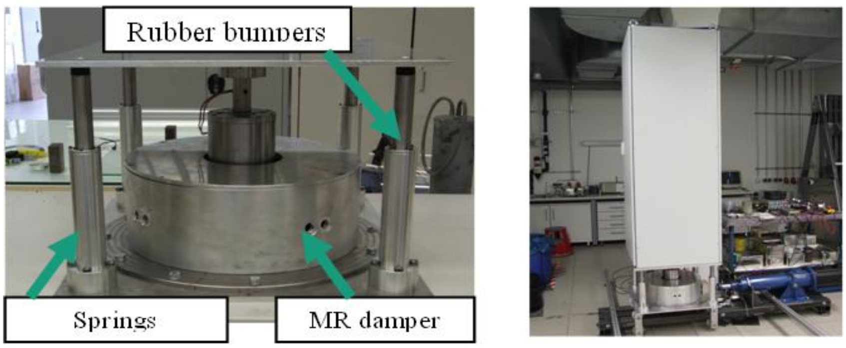

Figure 3. Semi-active system–MR damper for seismic protection and electrical control cabinet

4 PROJECT RESULTS AND DISCUSSION

4.1 Mock up seismic tests

A real size, two stories test house, called the “mock-up” (Figure 4), with dimensions 3.5 m X 3.5 m X 7 m height, with an innovative hybrid steel frame load bearing system (cold-formed and hot-rolled sections) completed with drywall systems (gypsum boards, Aquapanel cement board external walls, ETICS, gypsum fiberboard floors) and inclined roof with OSB sheathing, was tested to 3D earthquakes of ground acceleration up to 1.08 g.

The design of the mock-up has been optimized by WBI, the materials and construction were undertaken by KNAUF Gypsopiia ABEE. The tests were performed using the shaking table - 4mx4m plate and max. 100 kN weight of specimen – of the Laboratory for Earthquake Engineering of the National Technical University of Athens, Greece. During testing, several prototype recording systems were employed. Accelerometers have been used for the monitoring of the seismic motion. The MR-damper, the temperature-humidity-vibration recording system and the wireless broadband system of EMPA, Switzerland, have been tested during the seismic campaign.

The characteristic elements of the specimen (walls and floor/ceiling) were assembled on the bare frame step by step, and totally 3 series of shaking table tests were performed. Initially, the bare steel frame (Specimen I) was tested (1st series of tests). Then the floor and ceiling were fixed and the new model (Specimen II) was tested (2nd series of tests). Finally, the walls were assembled on Specimen II and the new model (Specimen III) was tested (3rd series of tests) (Figure 4). The primary test for each specimen was a biaxial XZ/ YZ/ triaxial XYZ earthquake test using artificial time histories generated to match the Hellenic elastic design spectrum with base acceleration 0.24g; soil class B and damping 4%. Several tests were performed with the acceleration of the shaking table to be scaled step-wise in order to verify and estimate the behavior of each model under earthquake excitation. Dynamic characteristics of each system were assessed through sine sweep tests before and after earthquake tests.


(a): Specimen II


(b): Specimen III

Figure 4.View of “mock up” on the NTUA.LEE shaking table: (a): Specimen II; (b): Specimen III.

Specimen with floor decking, roof sheathing and drywall systems (Specimen III) sustained severe triaxial earthquakes up to an input acceleration of 1.08g and its response was characterized as “elastic”. The specimen did not lose any significant global resistance (no strength reduction or stiffness degradation occurred) and no visible damage was observed after inspection at the end of testing procedure. It should be noted, for comparison reasons, that the highest ground acceleration ever recorded in Greece was less than 0.5 g; the ground acceleration of the IZMIT, Turkey earthquake was about 0.65 g; and the ground acceleration of the recent CHILE earthquake was less than 0.8 g. On the other hand, an increase of dissipated energy was observed during strong earthquake tests with base acceleration 0.72g, 0.84g, 0.96g and 1.08g. This increment could be attributed to the friction of the boards on the metal studs.

4.2 Construction of full scale demo house

The results of the I-SSB project are demonstrated in a full-scale family house (Figure 5) constructed at the industrial premises of KNAUFABEE in Amphilochia, Greece. The house has been designed by IKODOMIA, Cyprus and WBI to sustain extreme loads of wind, vibrations and earthquake (compliance with Eurocode 8). The two-storey, 152 m^2, residential house represents a typical Greek family two-storey dwelling (Figure 6), with a typical residential arrangement plan (ground floor: kitchen, office and living room, first floor: master and auxiliary bedroom). The house is constructed using a load-bearing heavy steel skeleton with CFS members combined with drywall systems (multi layered plasterboard assemblies), in accordance with earthquake, fire-resistance, thermal and sound insulation requirements. The external walls of the house (cement boards with thermal insulation) are multi-layered, consisting of (from the interior to the exterior) two 12.5 mm plasterboards, a 182.5 mm void (allowing space for the steel frame and plumbing), a 12.5mm plasterboard, a layer of 80 mm rock wool, a 12.5 mm cement board and a final layer of 50 mm EPS polystyrene. The internal walls consist of two 12.5 mm plasterboards, a layer of 80 mm rock wool and two 12.5 mm plasterboards. Special boards have been used for walls, floors and roof (e.g. thermoboards, fireboards, smartboards).

The I-SSB house has been equipped with the sensors and actuators developed in the frame of the project. Vibration, temperature-humidity-smoke sensors, three PZT-fibre based 3D sensors for the monitoring of man-induced vibrations and earthquake and the MR-damper for seismic protection as well as a geo-phone and a surveillance camera have been installed. A wireless sensory network has been established that consists of the above sensors measuring various parameters and three readers that read the data flow from the sensors. The data is transmitted through a WiFi router, with the data being routed to the point of storage. The data collection server can be accessed via web UI to view and analyse data (http://83.69.222.162:9900/issb/).

Figure 5. The I-SSB project demonstration house in Greece

5 CONCLUSIONS

Mechanical strength, thermal insulation, fire-resistance, ease of application and dynamic response to external perturbations make drywall, steel-frame construction an attractive option for house building, especially in areas at risk from events such as earthquake or fire. Such structures are easy and fast to erect and very flexible in configuration.

The I-SSB project demonstrated that it is possible to construct lightweight buildings using advanced design procedures and drywall systems that ensure added safety, improved comfort and reduced environmental impact. New types of plasterboards with improved ability to withstand extreme conditions occurring during earthquake or fire have been developed and successfully tested in the frame of the project. Sensors and actuators together with an embedded wireless network to monitor and control dynamic oscillations within the buildings have been developed and implemented. The seismic tests performed in a mock up structure based on the I-SSB concept and the monitoring results from the full-scale residential house designed to sustain extreme loads of wind, vibrations and earthquake and constructed in Greece demonstrated the excellent anti-seismic behavior of drywall/steel-frame construction. Both have been equipped with innovative sensors/actuators to reduce man-induced vibrations, control noise and seismic activity.

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