Investigation of the ultimate behaviours and FEA of wood stressed-skin panels

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ABSTRACT: In Australia wood has a significant role in the building industry, particularly in individual housing. With stressed-skin panels (SSP) new opportunities can be generated for use of timber in multi-storey residential, industrial, commercial and public buildings. To achieve this, the serviceability and ultimate resistance of SSP elements needs to be understood. The subject research program aims to investigate the load/stress distribution in SSP and the composite characteristics of SSP for service and ultimate resistance with laboratory tests and finite element analysis (FEA).

After introducing SSP technology, this paper presents an overview of the investigations undertaken to date whereby the analysis of the laboratory tests is being carried out and FEA has just been started. The analysis of the test results yet completed has shown that the serviceability, ultimate resistance, load/stress distribution and composite characteristics have matched the theoretical assumptions well. First FE models have given satisfactory responses with respect to SSP behaviours. This paper has two focuses of discussion; the ultimate responses of the laboratory investigation and the primary outcomes of FEA.

1 INTRODUCTION

Wood is very versatile and adequate building material. With respect to floor systems, timber products available on the market enable light and strong structures. Combining the floor components carefully and building composite properties further enhance the reliability and capacity of wood solutions.

In the early 2000's, lightweight floor systems were thoroughly investigated in Switzerland (Gerber & Sigrist 2002). The focus of this research was set on the material used, the construction techniques and the structural responses. Groups of floor systems, based on structural performances, and design aids such as abacuses and tables represented the outcomes of the project. This study highlighted that research was needed on issues such as reliability of the design model, prediction of the long-term behaviour and load/stress distribution. The project was completed in summer 2002 and formed the foundation of the PhD research of the first author.

The subject research addresses some of the issues identified in the Swiss project. It aims to obtain a better understanding of the serviceability and ultimate resistance of floor systems built with stressed-skin panel (SSP) technology. With both the Swiss and Australian projects, the collaboration with industry was sought. This had significant impacts on the definition of the research plan. However, the involvement of industry partners increases the applicability of the findings of both projects.

2 SSP TECHNOLOGY

Wood floor systems are generally built with joists and superimposed layers. In conventional floors the joists and panels are connected with mechanical fasteners such as nails or screws. Such connections have a low stiffness and shear resistance and thus restrict the contribution of the superimposed panels to resisting loads. Therefore the material strength properties of the panels are inefficiently used and only a limited perpendicular load/stress distribution is achieved and as such permitted by the Australian code (AS1720.1–1997, 1997).

Composite floor such as SSP are obtained when the connections between the joists and the panels are resistant to shear and impede slip. To obtain these composite actions the skin-to-joist connections are built with nail-gluing or screw-gluing techniques (Gerber 2003, Kairi et al. 1999) i.e. combinations of mechanical fasteners and structural adhesives such as defined by the code (AS/NZS 4364:1996, 1996).

As a consequence of the assembly higher stiffness, the contribution of the superimposed panels is enhanced, the material strength properties are used optimally i.e. the panels work as membranes and take on high stress, and the load/stress distribution in the floor structure is improved.

In Table 1 the constructive and structural differences between conventional wood floors and SSP are compared.

Table 1: comparison of wood floor systems

		Conventional floor systems	Stressed-skin panels (SSP)
Construction parameters	Skin-to-joist connection	Non-structural	Structural
	Composite characteristic of floor structure	None	Yes
Structural responses	Stiffness of floor structure	—	↑
	Load/stress distribution in floor structure	—	↑
	Ultimate resistance of floor structure	—	↑

SSP composites can combine a wide range of wood and non-wood products (Gerber & Sigrist 2002, Kliger 1993, 1995). Because of this, SSP constructions can, depending on the characteristics offered, meet the requirements of multi-storey, industry, commercial and/or public buildings. Implementing engineered wood products gives floor systems with reliable structural properties and high dimensional stability. Built with SSP elements, floors provide excellent horizontal bracing to the construction providing that the connections between the SSP elements and the connections of the floor to the bearing walls resist shear. In addition SSP systems offer architectural benefits such as longer span, lower profile and higher quality finish i.e. visual aspect of the ceiling and/or flooring. Finally, a high degree of prefabrication is possible with SSP; hence the time of erection on site can be shortened.

3 STATE OF THE ART OF SSP DESIGN

In Australia the current code edition timber design, AS1720.1–1997, permits SSP structures but gives only minimal directives for their design. From a research on low profile floors, the Plywood Association of Australasia (PAA) published a technical brochure giving construction requirements and span tables for T stressed-skin floor systems built with plywood panels (Plywood Association of Australasia Ltd 1998).

In Europe many countries have adapted their national codes to Eurocode 5 (1995) – EC5. In EC5, SSP elements are regarded as agglomerates of composite entities i.e. each joist is associated with a portion of the panel forming C or I cross-section. EC5 guidelines apply to plywood, chipboard and fibreboard skins.

From America design methods consider SSP elements as whole units (Faherty & Williamson 1999). Most methods require plywood skins.

3.1 *Design concept*

SSP elements can be either two- or three-component composites. The joists form the cores to which the skins or portions of them participate. For the subject research, because of the absence of proper guidelines and design method in AS1720.1–1997, EC5 specifications were adopted to predict the behavioural responses of SSP composite.

3.2 *Composite characteristics*

3.2.1 *Definition of the tributary width of the skin*

EC5 specifies that the tributary width is related to the span of the floor, the material, thickness and compressive buckling propensity of the panel (Table 2). Two different calculi are imposed on SSP elements i.e. considering edge and interior joists respectively.

Table 2: estimation of the tributary width of the skin

skin material	**shear lag**	**plate buckling**
plywood (grain direction of outer plies):		
▪ parallel to the joists	0.1 *l**	25 h_f**
▪ perpendicular to the joists	0.1 *l*	20 h_f
oriented strand board (OSB)	0.15 *l*	25 h_f
particleboard/fibreboard with random fibre orientation	0.2 *l*	30 h_f

* *l*: span; ** h_f: thickness of skin

3.2.2 *Estimating of SSP static characteristics*

SSP elements are fully composite constructions can be applied. Firstly the skin contribution is estimated; secondly the characteristic values of the composites are calculated with the transformed-section method (Gere & Timoshenko 1999). The neutral axis of the cross-section is obtained with Eq. 1 and 2, in which the modular ratio (Eq. 3) is introduced.

$$E_1\int_1 ydA + E_2\int_2 ydA + \ldots + E_n\int_n ydA = 0 \qquad \text{(Eq. 1)}$$

$$\int_1 y\ dA + \int_2 yn_2\ dA + \ldots + \int_n yn_n\ dA = 0 \qquad \text{(Eq. 2)}$$

$$n_2 = \frac{E_2}{E_1}\ ;\ \ldots\ ;\ n_n = \frac{E_n}{E_1} \qquad \text{(Eq. 3)}$$

3.3 *Stress verification*

Stress is estimated with Eq. 4. To consider the material "oneness" of the transformed-section, the modular ratio (Eq. 3) is introduced into Equation 5 when verifying the stress across the SSP cross-section.

$$\sigma_{x1} = \frac{M}{I_T} y \qquad \text{(Eq. 4)}$$

$$\sigma_{x2} = \frac{M}{I_T} y \, n_2 \; ; \; ... \; ; \; \sigma_{xn} = \frac{M}{I_T} y \, n_n \qquad \text{(Eq. 5)}$$

Stress verifications are imposed on every structural member of the SSP composite. Working as membranes, the skins are verified with respect to bending and normal stresses (Table 3). The joists work as bended elements and are checked as such. To end with shear stress is checked, since this action is particularly relevant to the integrity of the bond at the I-joist web-to-flange and SSP skin-to-joist connections.

Table 3: stress verifications of the skin

location of the stress verification	**type of stress**
stress at the external fibre of the skin	bending stress
stress at the centre of the skin	compressive/tensile stress
shear stress at the web-to-flange and skin-to-joist connections	shear stress

4 SCOPE OF PHD RESEARCH

The subject research program involves a thorough study of SSP technology. The focuses were set on the load/stress distribution in SSP and the composite characteristics of SSP at service and ultimate limits. The research has been divided into three major stages:

1. Study of analytical models and design methods.
2. Laboratory investigations to define the serviceability (stiffness, stress/load distribution) and ultimate response of full-scale SSP elements with different boundary conditions.
3. Elaboration of design aids such a calibrated FE model and design recommendations.

The first phase of the project aimed to define the states of the art of SSP technology and of the research in this area with focus on Australian building practises. Theoretical models of SSP behaviour and design methods applied to SSP were also studied.

The laboratory investigations had two main goals; to verify and legitimate the validity of the design model that had been adopted and to collect relevant data for the calibration of the FE model and for the definition of the design recommendations. At the time of this paper (January 2005), the analysis of the laboratory investigation is being completed.

In the final stage of the research, a FE model is being developed and calibrated according to the results of the laboratory testing. The FE model may be used for optimisation works. Finally, design guidelines for SSP systems will be proposed.

5 THEORETICAL ASSUMPTIONS

5.1 *Behavioural assumption of the skin*

The stress distribution in the skin determines the magnitude of the tributary width of the panel. Raadschelders & Blass (1995) proposed that the stress distribution in the skin can be described by a geometric function characterised by the orthotropic properties of the wood panel i.e. the Poisson's ratio of the skin material defines the profile of the distribution curve. Figure 1 illustrates the stress distribution in the skin(s) of T and box section SSP.

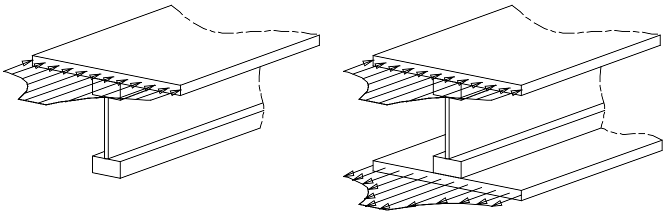


Figure 1: stress distribution in the skin(s) of SSP

5.2 *Failure assumption of SSP composites*

Wood is generally regarded as brittle material and as such to experience fragile moduli of rupture (MOR). However, complex composites can, under particular circumstances, show some ductility. Brunner et al. (2001) proposed that when the tensile side possesses an enhanced tensile strength – with or without reinforcement – ductility occurs because of wood plasticity in compression. Such MOR can be expected with SSP composites, particularly with box-sections wherein the tensile side is structural plywood.

For the laboratory investigation, the full-scale SSP elements were built with I-joists with plywood web. Shear failures in the web can induce non-linear behaviours; thus the potentiality that SSP specimens experience non-linear MOR is increased.

6 INVESTIGATION ON FULL-SCALE SSP

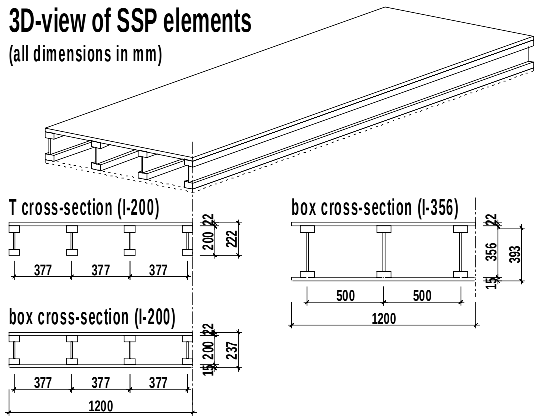
The laboratory experiments on full-scale SSP represent a comprehensive and methodical investigation of 26 specimens under different punching and line load locations with different boundary conditions. The aim was to obtain a complete set of data with respect to behavioural responses of SSP composites such as serviceability, load/stress distribution, composite characteristics and ultimate resistance. The data collected from the laboratory test will as well be used to carry out the fine calibration of the FE model and to define design recommendations.

6.1 *Research plan – specimen parameters*

The Australian construction standards for floor systems and the use of competitive engineered wood products defined the variable parameters of the research plan (materials and dimensions). 200 and 356mm I-joists formed the cores of the SSP test specimens in order to address the domestic housing sector and the industry, commercial and public buildings respectively.

Table 4 summarises the variable parameters of the research plan.

Table 4: variable parameters of the research plan

Cross-sections of the specimens (Figure 2): ▪ T cross-section. ▪ Box cross-section.    Figure 2: full-scale SSP specimens
Engineered wood products of the structural members: ▪ 200* & 356**mm I-joist. ▪ plywood. ▪ particleboard. ▪ oriented strand board (OSB).
Adhesives of the skin-to-joist connections: ▪ rubber based adhesive (RBA). ▪ polyurethane (PUR).

* 3700mm span; ** 6600mm span

By combining the variable parameters, 14 test series were obtained whereby four of these series counted three samples. These replications enabled to quantify the response variability; thus, enhancing the reliability of the laboratory testing.

6.2 *Boundary conditions*

6.2.1 *Integrity of SSP element – alteration*

Discontinuous skins caused by the inclusion of or as a result of misconstruction may modify the behavioural responses of SSP composites. Presumably the alterations change the load/stress distribution in SSP and the composite characteristics of SSP.

The investigation on alteration aimed to study and quantify the effects of discontinuous skins on the serviceability and ultimate resistance of SSP floor systems. For this investigation, the panel of the T section specimens and both panels of the box section specimens were cut perpendicularly to the joists in the maximum bending moment zone i.e. 150mm away from mid-span.

The effects of alteration were studied with specimens built with 200 and 356mm I-joist.

6.2.2 *Support conditions – buckling restraint*

Restraining lateral buckling of the joists at the supports is assumed to have a stabilising effect and thus influences on the serviceability and ultimate responses of SSP elements.

To investigate the magnitude and characteristics of the buckling restraint, plywood boards were nailed at each end of some specimens. Four strain gauges were purposely arranged on the skins by the supports in order to identify and quantify the effects of the restraint.

The study of the influences of restraining lateral buckling was carried out on 356mm I-joist specimens only.

6.3 *Testing infrastructure*

The tests were carried out in a testing rig that allowed the set-up of many loading configurations (Figure 3). Such polyvalence and flexibility of the rig setting was important because of the number of tests and of loading locations. Because of this the test completion could be optimised significantly.

Figure 3: SSP floor element in testing rig

In order to meet the data acquisition requirements imposed by the scope of subject research the specimens were instrumented with numerous apparatuses such as load cells, linear variable differential transducers (LVDT) and strain gauges.

7 RESEARCH RESULTS

7.1 *Discussion on the modulus of rupture*

Wood structures are highly expected to present brittle failures i.e. tensile ruptures of I-joist flange and/or skin. As discussed previously, it is in theory possible that some apparent ductility and/or non-linearity occur because of wood plasticity in compression and/or shear failure of the I-joist web.

The analysis of the laboratory tests is being carried out at the moment of writing (January 2005). Ultimate tests were completed on 22 specimens. Both types of MOR were identified by the analysis; thus confirming the theoretical assumptions. Brittle MOR (7 specimens) had two origins; the exceeding of the tensile strength of I-joist flanges in the maximum bending moment zone and/or of the shear strength of I-joist webs in the maximum shear zone. Non-linearity (15 specimens) was predominantly caused by shear failures of I-joist webs in the maximum shear area.

Figure 4 shows the graph of a brittle MOR of a T cross-section specimen. The failure was located at a knot in the tensile flange of an I-joist within the maximum bending moment zone (Figure 5).

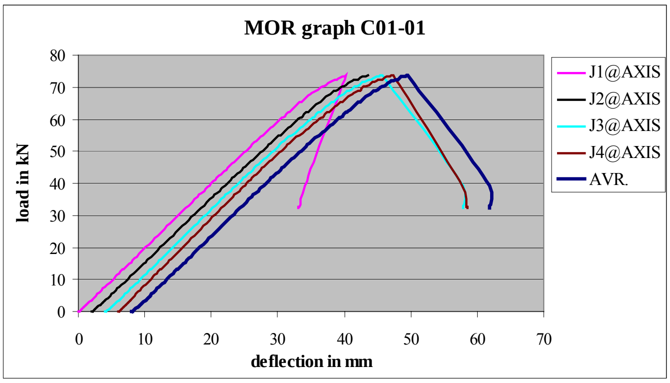


Figure 4: brittle MOR → failure of I-joist flange

Figure 5: tensile failure of I-joist flange

In Figure 6 the curve of a non-linear MOR of another T cross-section composite is illustrated. During the ultimate test, some I-joist webs experienced severe shear damage in the maximum shear zone (Figure 7). Eventually the specimen collapsed completely as a tensile failure happened in an I-joist flange within the maximum bending moment area (Figure 7).

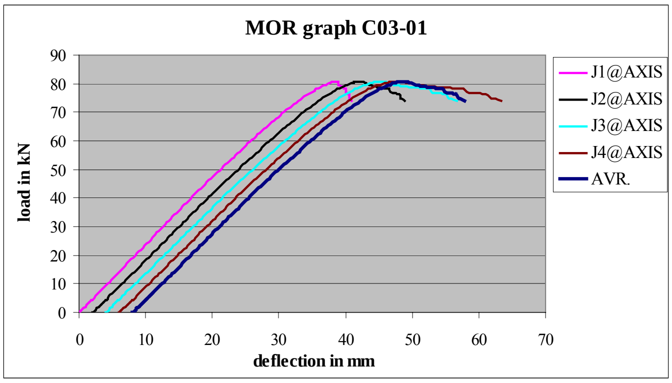


Figure 6: non-linear MOR → failure of I-joist web

Figure 7: shear failure of I-joist web (left) & tensile failure of I-joist flange (right)

7.2 *Discussion on the boundary conditions*

7.2.1 *Integrity of SSP element – alteration*

Discontinuous skins represent a severe weakening of SSP elements; particularly on the tensile side. Analysis of test results of the service limit state (SLS) showed that alterations changed the behavioural responses of SSP composites i.e. skin discontinuities caused noticeable loss of stiffness (Gerber et al. 2004). Presumably this phenomenon would also impact the ultimate limit state (ULS). It was therefore assumed that, because of the alteration, the specimens would have lower ULS.

Figure 8 to Figure 11 illustrate the effects of discontinuous skins on the ultimate resistance; whereby C05 and C08 were T and box cross-section composites respectively. The test results confirmed the change of stiffness that had been identified with SLS analysis (Gerber et al. 2004). In comparison to unaltered specimens, specimens with discontinuous skins showed ca. 10% loss of stiffness. With respect to ultimate strength the results forbade to identify any clear trends. Both specimens of series C05 had similar results; ultimate load of ca. 75kN. With series C08 a difference of ca. 10% was observed i.e. a divergence of little significance for timber structures.

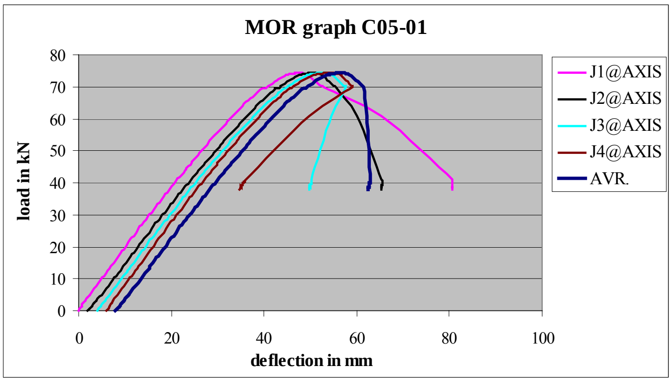


Figure 8: MOR of an altered T section specimen

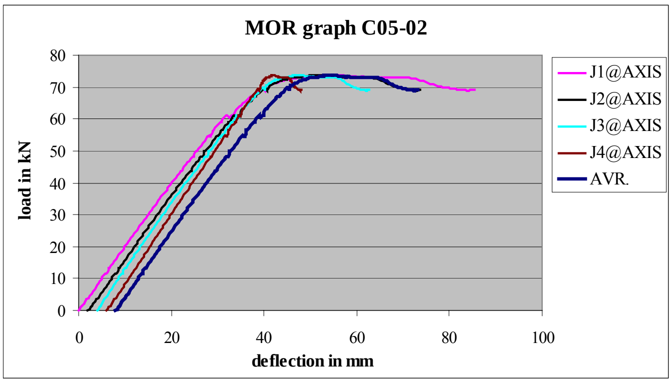


Figure 9: MOR of an unaltered T section specimen

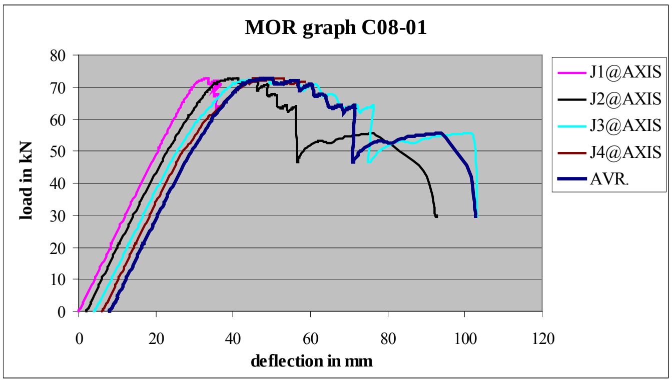


Figure 10: MOR of an altered box section specimen

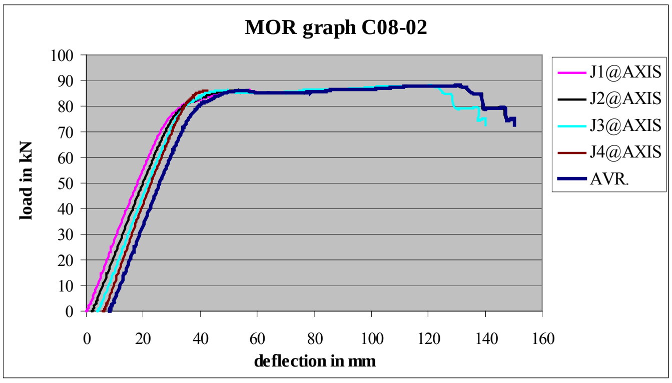


Figure 11: MOR of an unaltered box section specimen

As a result of alterations, major losses of stiffness were identified with ULS investigation confirming hereby the outcomes SLS analysis. No quantitative effects of discontinuous skins could be determined; presumably because most MOR originated in the I-joists i.e. web or flange failures. The SLS and ULS studies on alteration emphasise that to maximise the use of the qualities of SSP composites the excellence of the manufacturing and skin splicing is very important and must be ensured.

7.2.2 *Support conditions – buckling restraint*

Blockings at the supports reduce the buckling propensity of SSP elements. At SLS this increase of torsional stability improves the load/stress distribution by eccentric loading while by concentric loading the effect is naught (Gerber et al. 2004). ULS tests were carried out under concentric loading (4-point bending); thus, restraining buckling might have little effects on ultimate resistance. On the other hand at higher loading range it is assumed that I-joists experience increased lateral instability.

The study of buckling restraint was completed with box cross-section specimens built with 356mm I-joist. Figure 12 and Figure 13 present the ULS load-deflection curves of unrestrained and restrained specimens respectively. Both specimen constructions presented little difference of stiffness but equivalent ultimate resistances; C09-011 (unrestrained) failed at 130kN while C09-03 (restrained) failed at 129kN. Both MOR occurred owing to the exceeding of the shear strength in the splices of I-joist webs.

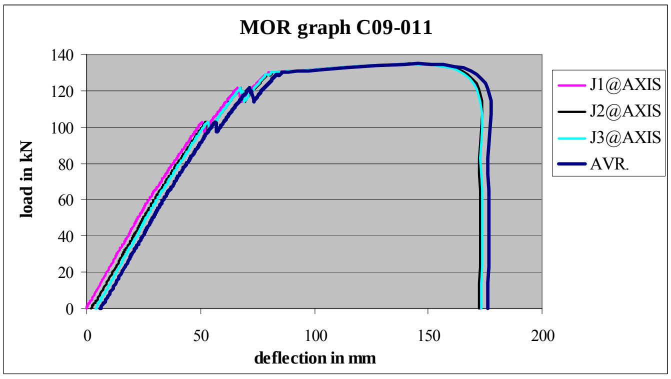


Figure 12: MOR of a specimen without buckling restraint (b)

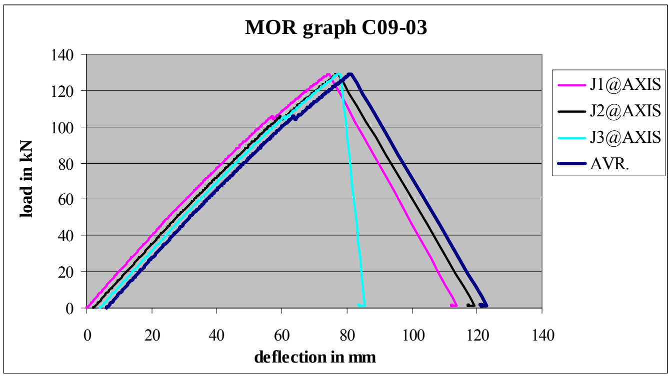


Figure 13: MOR of a specimen with buckling restraint

With an acceptable cost involved, restraining lateral buckling at the support stabilised the torsion propensity of the specimens and improved the load/stress distribution in the specimens. Thus, with eccentric loading the serviceability of SSP floor is significantly enhanced. More stability to lateral buckling also added some safety to ULS responses. This contribution could however not be quantified by the analysis of the MOR test results because of the concentric configuration of the loading.

7.3 *Conclusion*

The analysis of the laboratory test results showed that the ultimate resistance matched the theoretical assumptions in terms of behaviours and resistance values. ULS responses of the specimens also confirmed the conclusions of the serviceability analysis stated by Gerber et al. (2004). However, because the analysis has not been finalised yet (January 2005), it is therefore premature to draw final conclusions.

8 FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) helps to picture SSP behaviours and load/stress distribution in SSP. The FEA investigation focuses on service limit state i.e. the linear range of SSP elements.

8.1 *Elements of the FE model*

SSP floors are sophisticated constructions; thus, the elements of the model must be adapted to this complexity. The FE model was developed using ANSYS software package (ANSYS Inc. 2003). For the I-joist flanges and webs the 20-node solid element (SOLID186) was chosen. This element supports large deflection and important strains. The 6-node shell (SHELL93) was used for the skins. To complete the model, the skin-to-joist connections were modelled with matrix elements (MATRIX27); arbitrary elements of undefined geometry used for linking two nodes. To optimise the FEA investigation, the model was generated and solved with the help of command files.

8.2 *Materials of the FE model*

Solid wood and engineered wood products are orthotropic materials with distinctive properties in three directions mutually perpendicular; longitudinal, parallel to the grain; radial and tangential perpendicular to the grain. Each FE model required three to four orthotropic material matrixes. In ANSYS the elasticity matrix of orthotropic materials is defined by three moduli of Young (E_x, E_y , E_z), three Poisson's ratios (ν_{xy}, ν_{yz}, ν_{xz}) and three shear moduli (G_{xy}, G_{yz}, G_{xz}).

8.3 *FE model responses*

FEA has been started recently. The first phase aimed to verify the convergence and the agreement of the responses of the model. With this first phase FE model parameters such as the element types, the meshing and the connection arrangement were determined. To date the FE model has produced encouraging results; good convergence and shape responses. Figure 14 illustrates the deformed shape of the specimen. Compared to the laboratory test results the deflection obtained with the model is too low. In Figure 15 the stress distribution in the specimen is presented.

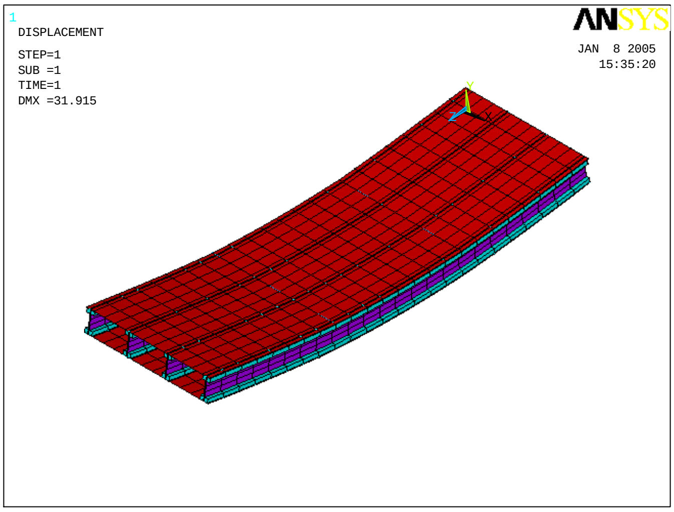


Figure 14: FEA results – 3D view of deformed specimen

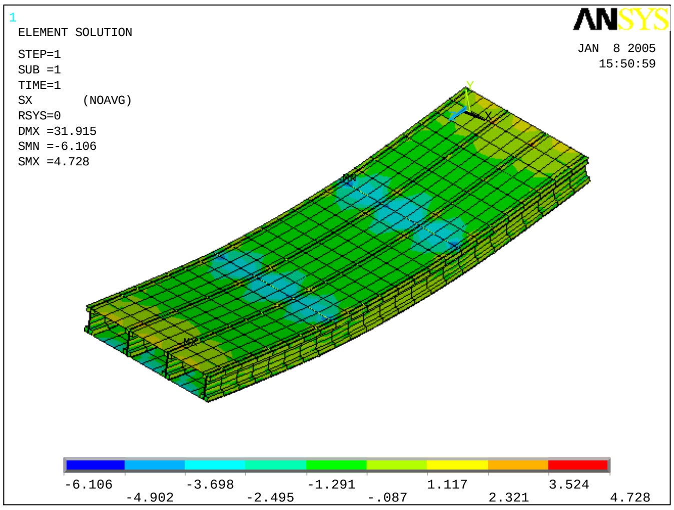


Figure 15: FEA results – 3D view of stress distribution

8.4 *Next stage of FEA*

In the next stage of FEA the model will be further tested with respect to convergence and response fittingness; deformed shape and load/stress distribution responses. Second, the FE model will possibly be calibrated so that the laboratory results of 4-point bending tests are matched. To obtain a complete comparison with laboratory investigation, FEA will focus on eccentric load cases. Next, FEA may be carried out to investigate optimisation of SSP floors such as material mix and constructive parameters. Finally, FEA may also be utilised to define and finalise design guidelines and recommendations.

8.5 *Conclusions*

At the moment FEA focuses on the linear behaviour of SSP. The initial stage of FEA has produced promising outcomes; demonstrating that the FE-model can be a helpful tool to picture and understand the stress/load distribution in SSP elements and to predict the design limit and serviceability of SSP floors. FEA may as well enable optimisation work of SSP constructions. However, because of the complexity of the composite cross-sections and materials of SSP floors some caution is necessary.

9 DESIGN RECOMMENDATIONS

To enable a smooth and reliable implementation of SSP technology, verified design aids and construction guidelines are necessary. For this reason the concept of supportive documentations will be defined based on the research outcomes. The finalisation and publication of such information is however beyond the scope of this research.

10 CONCLUSIONS

Overviews of a research into SSP elements, which forms the core of the PhD thesis of the first author, have been presented. As such, this paper gives an insight into the theoretical assumptions and discusses the results of the ULS aspects of the laboratory investigations. The analysis of ULS test results demonstrated that the ultimate resistance complied with the theoretical assumptions. Next FEA has been introduced. Encouraging results have been achieved during the initial stage of the FE modelling. With its magnitude this research has increased the understanding of SSP floors with respect to serviceability and ultimate resistance.

SSP technology possesses many advantages for the building industry, and it is essential for industry to capitalise on the results of research projects such as this one. To promote the benefits and encourage the use of SSP systems in the building industry significant efforts are required and will be made in order to educate carpenters and builders with the aim to achieve a "problem-free" and efficient implementation of SSP technology. It is therefore important to develop appropriate design and installation aids.

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