Accessible and reliable design of stressed-skin panels – an Australian perspective

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ABSTRACT: Stressed-skin panel (SSP) technology possesses many advantages and the subject research program has increased the understanding of SSP structures with respect to serviceability and ultimate resistance performance. In order for the building industry to capitalise on the results of this research, it is essential that the codes i.e. AS 1720.1−1997 (Australian Standard™ 1997) should embrace a design procedure enabling the use of the full potential of SSP systems. This paper outlines an amendment proposal to Section 5 of AS 1720.1−1997 that will enable designers to achieve a problem-free and efficient implementation of SSP technology. It focuses on the aspects of the tributary width of the sheathing and the stress determinations in the composite section. The proposed design procedure is both useable and straightforward to implement and satisfies requirements of structural safety and comfortable serviceability. It is based on a solid research background and relates to EC5 (European Committee for Standardisation 1995), which will necessitate some adjustments to fully comply with Australian design standard.

1 INTRODUCTION

In conventional floor systems (CFS) the joists and the superimposed panels are connected with mechanical fasteners such as nails or screws. Such connections have a low stiffness and limit the contribution of the superimposed panels to resisting loads, and rudimentary and often overly conservative design methods are applied. This approach results in inefficiently using the material strength properties and ignoring system aspects such as composite and two-way actions. In addition, it often leads to an increase in the cost of the structure.

In stressed-skin panels (SSP), the sheathing and joists are assembled compositely together i.e. the interlayers are manufactured using techniques that combine mechanical fasteners with an adhesive. The latter gives high stiffness to the assemblies i.e. impedes slip in the interlayers. Therefore, the material strength properties of the panels are better used. The composite and two-way actions are also improved.

In Australia the current code edition of timber design, AS 1720.1−1997 (Australian Standard™ 1997), gives only minimal recommendations about the design of SSP structures. Some directives are provided for determinations of stresses in the sheathing and interlayers but no guideline is given to estimate the tributary width of the panel, which represents a major aspect of SSP technology.

In 2002 a large-scale investigation of SSP assemblies manufactured according to Australian practice was launched at the University of Technology, Sydney. This research aimed to provide a better understanding of the behaviour of SSP structures such as the serviceability and ultimate responses, and to develop numerical approaches for predicting the behaviour of SSP decks. It also provides recommendations for amending Section 5 in future editions of the Australian code for timber design.

2 REVIEW OF THE LITERATURE

2.1 *Interaction in wood joist floors*

In joist floor systems, the joists and sheathing interact both by composite and two-way (load sharing) actions (Vanderbilt et al. 1974). This indicates that the sheathing does more than simply transferring loads to the nearest joist. It also acts compositely with the joists to some extent as well as forming continuous beams crossing the joists. Therefore, floors cannot be accurately designed solely on the mechanical properties of the joists and sheathing considered as series of individual bare elements.

Observed separately, the composite action primarily reduces the deflections of the joists i.e. the average floor deflection becomes smaller and the two-way action reduces the variation between the deflections of the joists i.e. the perpendicular deflection profile of the floor becomes smoother. Optimising the composite and two-way actions is therefore paradoxical. The composite action is maximised when the joist orientation and the strength axis of the sheathing concur whereas the optimum two-way action is obtained when the joist longitudinal axis and the strength axis of the sheathing cross orthogonally.

2.2 *Composite action*

Composite action occurs whenever the interaction between two components results in a shift in their neutral axes (for flexural stress) towards one another. Under full composite action, the neutral axes of the section components coincide. The first and second moduli of the section area increase, thus reducing the stress in the section members and increasing the stiffness of the section respectively. The amount of composite action depends on the relative size and stiffness of the sheathing and the joist, the stiffness of the interlayers and the continuity of the sheathing.

Nokelainen (2000) noted that glued floor constructions have high stiffness and bending strength, and no interlayer slip. In an attempt to quantify the stiffness improvement infers by bonded interface, Nokelainen showed that floor systems without connection and with mechanical fasteners reach about 25% and 45% respectively of the stiffness of fully composite systems.

2.3 *Two-way action*

The sheathing also forms a continuous multiple span cross-beam perpendicular to the joists. It carries the loads to the joists and distributes the load among the joists, resulting in "two-way" action. Studies on this mechanism indicated a smoothing effect on the deflections of the joists – less variation between the joists – in floor systems.

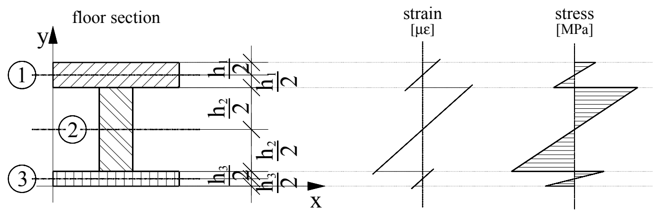
With increased stiffness of the sheathing in the direction perpendicular to the joists, the two-way action dominates and the joist deflections become more uniform i.e. the variation of the joist deflections is reduced. Therefore, the orientation of the strength axis of the panels to the joists also affects the two-way action. Decreasing the sheathing stiffness, such as generated by gaps, reduces the effectiveness of the two-way action.

Load sharing or lateral load distribution also corresponds to the ability found in repetitive parallel member system ─ wood joist floor systems included ─ to transfer load away from the loaded member to the adjacent members through the flexural stiffness of the sheathing. Load sharing greatly depends on the bending stiffness of the sheathing and to some extent the joist properties, especially the mechanical variability. Wolfe (1990) noted that load sharing is effected by various interactions of the floor aspects such as the size effect, mutual restraint and bridging.

3 WOOD JOIST FLOOR TECHNOLOGY

3.1 *Conventional floor systems (CFS)*

CFS invariability comprise two or three horizontally arranged layers (in top-down order): 1) the flooring, 2) the joists (e.g. at 450mm centres), and 3) the ceiling. The joists and the panels are connected with mechanical fasteners at nominal spacing. Such connectors have low stiffness and limited shear strength, and slip occurs in the interlayers. Therefore in CFS, the contribution of the panel(s) to resist loads is limited and the simple beam theory (SBT) cannot be applied. Figure 1 depicts a composite section with interlayer slip.



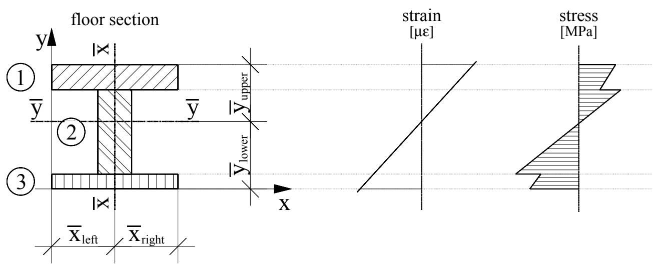
where $E_1 < E_2$ and $E_3 < E_2$.

Figure 1: Strain and stress distribution across the floor section ─ slip in interlayers

For CFS design, interactions between the structural members are generally ignored. The floor members are confined to distinct roles to which they are designed specifically. The validity of this practice is questionable because it represents a grossly simplified assumption and is very conservative. Despite this, current practice for CFS design ─ as such stipulated in many codes ─ still ignores any interaction between the system members (British Standard 2004). Other codes account for the floor acting as a unit of repetitive parallel members, especially the bridging effect of the sheathing. In Australia, the bending strength of the joists may be increased up to 24% because of bridging (Australian Standard™ 1997). However, these practices ignore any contribution of the panel(s) to the structural performances of the joists. Furthermore, this factor can only be applied for uniformly distributed loads, but not for point loads.

3.2 *Stressed-skin panels (SSP)*

Panels longitudinally and/or orthogonally reinforced with stiffeners combine light weight with high strength. The versatility of this technology has been recognised in many fields, such as aeronautics, vehicle design and civil engineering. In lightweight floor structures, the superimposed structural panels are glued to the joists with structural adhesives forming a composite assembly i.e. SSP composites. The structural performances of SSP assemblies depend upon the composite action, which efficiency relies on the connection strength. In many cases, the interlayers are built combining mechanical fasteners and adhesives. In order to minimise the risk of bond failure, structural adhesives, such as defined in AS/NZS 4364:1996 (Australian/New Zealand Standard™ 1996), must be favoured. These adhesives have known and reliable properties and meet the requirements of SSP technology by generating bonds with strong shear resistance and high rigidity. Raadschelders & Blass (1995) proposed that gluing gives skin-to-joist connections of infinite stiffness. As a result of this, a linear strain distribution may be assumed over the depth of the SSP section and SBT can be applied. Figure 2 depicts a composite section with full composite action.



where $E_1 < E_2$ and $E_3 < E_2$.

Figure 2: Strain and stress distribution across the floor section ─ no slip in interlayers

To generate skin continuity, splicing of the panels between the joists may be desirable. With today's technology, some panel suppliers are able to manufacture engineered wood panels of "unlimited" length and increased width.

SSP floors can also work as horizontal diaphragms. The sheathing acts as the web and resist shear forces, while the joists act as flanges and resist flexural moments. The connections between the sheathing and the joists must be shear resistant. Thus for design, this action in the interlayer must be superimposed to the shear stress induced by the flexural moment of the floor system under load normal to its plane. Further, the connections between the floor systems and bearing walls, and between the elements of prefabricated floors must be shear resistant.

4 ASPECTS OF SSP DESIGN

4.1 *Section properties of SSP*

Estimating the properties of SSP systems, on which the strength and serviceability of the structure depend, forms an important stage of SSP design. The joists are web members with which the skins or portions of them act compositely. The strength and slip modulus of the interlayers also affect the properties of SSP sections. Because slip is impeded, SSP assemblies exhibit fundamental static principles such as SBT and uniformly linear strain distribution. Therefore, the section properties can be estimated using the transformed-section whereby the neutral axis of the cross-section is obtained with equations (1) and (2) in which the modular ratio (3) is introduced.

$$E_1\int_1 ydA + E_2\int_2 ydA + \ldots + E_n\int_n ydA = 0 \qquad (1)$$

where E_n = modulus of elasticity of a section member [MPa], y = y-axis (vertical) distance [mm], and A = area of a section member [mm^2].

$$\int_1 y\, dA + \int_2 yn_2\, dA + \ldots + \int_n yn_n\, dA = 0 \qquad (2)$$

where n = modular ratio.

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

Subsequent section properties can be calculated using transformed-sections.

4.2 *Tributary width of the skin(s)*

The tributary width represents the portion of the skin that acts compositely with a joist. This corresponds to the segments of the panels that take normal stresses (Figure 3), which develop in the sheathing under bending moment action, and contribute to the stiffness of the structure. Because of shear deformations, the distribution of this normal stress is not uniform in the centre plane of the cantilevered – unsupported – portions of the skin(s) (Raadschelders et al. 1995).

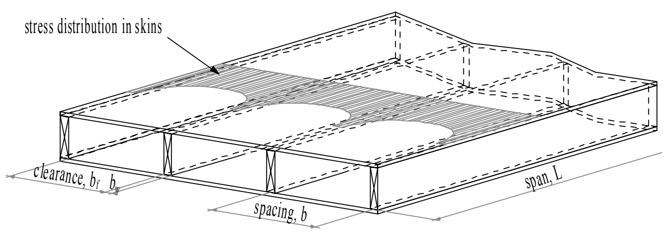


Figure 3: Stress distribution in the skin(s) of SSP deck

The contribution of the skin(s) is not identical at every location along the span e.g. at the support and at mid-span where limited and full contributions are expected respectively. Amana & Booth (1967) reported that the panel is fully contributing only a short distance away from the ends of or gaps in the sheathing. The contribution of the sheathing is also affected by aspects such as the axial stiffness of the panel, the slip modulus of the interlayers, and the presence of gaps. A tendency for flange buckling under compression may also limit the contribution of the sheathing. Thorough analysis can be carried out to assess the critical buckling load but keeping joist clearances less than twice the tributary width generally avoids instability.

Estimating the tributary width accurately can prove complex and requires material data, which is not always available even in specialised literature. The magnitude of the tributary width is based on the stress distribution in the sheathing, which is not linear because of shear deformations (Raadschelders et al. 1995), and is influenced by the mechanical properties of the panel. In the 1960's, Möhler et al. (1963) carried out works on the tributary width of plywood sheathing and derived a geometric function (5) for the shear lag accounting for the elastic orthotropic properties of the panel and the geometric dimensions of the floor. Therefore, (5) is characterised by the moduli of elasticity (E), the shear modulus (G) and the Poisson's ration (μ) and by the span of the floor (L) and the joist clearance (b_f). Further, the buckling propensity of the compression flange and the shear deformation in the panel(s) are also considered.

$$w = w_{ef} = b_w + b_{ef} \tag{4}$$

whereby the shear lag is:

$$b_{ef} = 2L\frac{\left(\lambda_1 \tanh\alpha_1 - \lambda_2 \tanh\alpha_2\right)}{\pi\left(\lambda_1^2 - \lambda_2^2\right)} \tag{5}$$

in which the coefficients are:

$$\alpha_1 = \frac{\lambda_1 \pi b_f}{2L}, \qquad \alpha_2 = \frac{\lambda_2 \pi b_f}{2L} \tag{6a, b}$$

$$\lambda_1 = \sqrt{a + \sqrt{a^2 - c}}, \qquad \lambda_2 = \sqrt{a - \sqrt{a^2 - c}} \tag{7a, b}$$

$$a = \frac{E_y}{2G} - \mu_{xy}, \qquad c = \frac{E_y}{E_x} \tag{8a ,b}$$

where w = tributary width [mm], b_{ef} = shear lag [mm], L = span of the SSP structure [mm], μ_{xy} = Poisson's ratio of the panel, E_y & E_x = moduli of elasticity of the panel [MPa] *(x & y = perpendicular and parallel to the joist axial direction respectively)*, and G = shear modulus [MPa].

For more convenient design, engineers have access to methods that consider an effective width in which the stress is uniformly distributed (Amana et al. 1967). The tributary width is approximated by equating the stress under the geometric curve of the non-uniform distribution to a fictive uniform rectangular distribution (Figure 4). With that assumption the panels take equal amounts of stress and the real and idealised composite beams have equivalent flexural resistance.

Design codes provide procedures and directives to approximate the magnitude of the skin(s) contribution about the joists. However in Australia, AS 1720.1−1997 gives no guideline for estimating the tributary width. Therefore, the directives of EC5 (European Committee for Standardisation 1995), which have been used in the subject research, are recommended and presented hereafter.

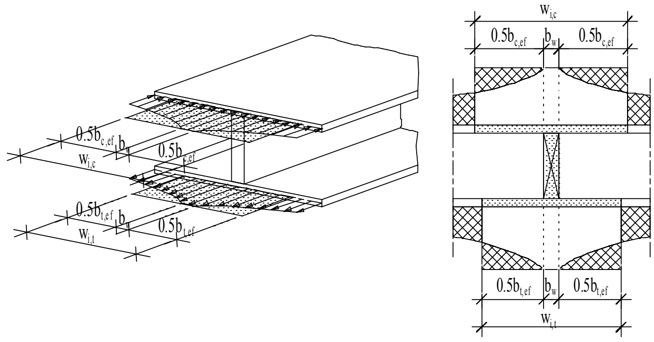


Figure 4: Stress distribution in the skin(s) and tributary width of the skin(s)

In EC5 procedure, the tributary width is governed by the joist clearance, b_f, the shear lag and the buckling propensity, and by the joist clearance and the shear lag for the compression (9) and tension (10) skin respectively. The shear lag is estimated considering the span, L, and the shear lag factor of the panel, C_{SL}. The buckling stability is governs by the thickness of the panel, h_f, and buckling coefficient of the panel, C_{PB}.

$$w_{EC5,c} = b_w + \min b_{c,ef} = b_w + \min\begin{vmatrix} b_f \\ c_{SL}L \\ c_{PB}h_f \end{vmatrix} \tag{9}$$

$$w_{EC5,t} = b_w + \min b_{t,ef} = b_w + \min\begin{vmatrix} b_f \\ c_{SL}L \end{vmatrix} \tag{10}$$

where w = tributary width [mm], c_{SL} = shear lag factor, c_{PB} = plate buckling factor.

The effectiveness ratio (11a, b) of the sheathing contribution obtained with Möhler et al. (1963) and EC5 equates the values of the estimates (cantilevered portion of the panel: b_{ef}, $b_{t,ef}$ and $b_{c,ef}$) and the joist clearance, b_f.

$$\frac{w_{Möhler} - b_w}{b_f}, \qquad \frac{w_{EC5} - b_w}{b_f} \tag{11a, b}$$

Considering the construction parameters of the specimens of the subject research, examples of effectiveness ratios of compression skins is presented in Figure 5. The curves agree well with low joist clearance to span ratios ($b_f/L \leq$ *ca. 0.1*) but significantly diverge with higher b_f/L ratios. They also demonstrate that the EC5 is more conservative than Möhler et al. Figure 5 also shows that with EC5 the panel contribution is firstly governed by the joist clearance (plateau of the curves) and secondly by the shear lag (exponential decay portion of the curves).

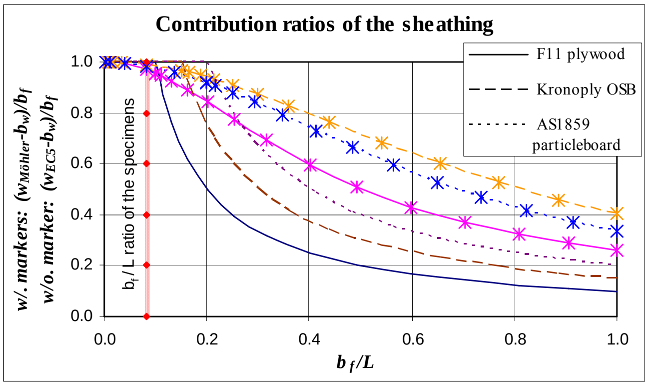


Figure 5: Effective contribution of the skins

Most SSP systems have low b_f/L ratios. Raadschelders & Blass (1995) proposed that most cases are contained under 0.3. EC5 represents a sound method for this group of SSP systems and the EC5 guidelines also suit the Australian practice. Therefore accommodating EC5 directives in AS 1720.1−1997 is recommended.

4.3 *Stress determination*

In most situations, floor systems are in flexural state. This generates bending, normal and/or shear stresses in the members and interlayers of SSP structures. After Desler (2002), the greatest portion of the bending stress is taken by the panel(s) while the joists take the shear stress. Elsewhere, Gerber & Sigrist (2002) proposed that the skin(s) experience(s) an interaction of normal and bending stresses. Shear failure may also appear inside the sheathing (Desler 2002). Further, normal and rolling shear stresses develop in the interlayers.

Design guidelines of AS 1720.1−1997 (Australian Standard™ 1997) suggests that the SSP components should be verified with respect to bending stress for the skin(s) and bending and shear stresses for the joists. In Section 5.6 of AS 1720.1−1997, requirements for shear resistance of glued interfaces are given and a table indicates modification factors for the interlayers. It also appears that AS 1720.1−1997 directives only apply to SSP systems with plywood sheathing. Table 1 summarises the verifications imposed by AS 1720.1−1997.

Table 1: Stress verifications of SSP — AS 1720.1−1997

Location of the stress verification		***Type of stress**
Upper skin	(Upper) extreme fibre	Bending
Upper interlayer		Rolling shear
Stringer	Upper extreme fibre Axial fibre Lower extreme fibre	Bending Shear Bending
Lower interlayer		Rolling shear
Lower skin	(Lower) extreme fibre	Bending

*for single span deck in flexural state.

EC5 (Table 2) specifies that normal stresses, and bending and shear stresses should be verified at the axial fibre of the sheathing and in the joists respectively. The design is completed by verifying the strength of the interlayers.

Table 2: Stress verifications of SSP — EC5

Location of the stress verification		***Type of stress**
Upper skin	Axial fibre	Compression
Upper interlayer		Fastener load
Stringer	Upper extreme fibre Axial fibre Lower extreme fibre	Bending Shear Bending
Lower interlayer		Fastener load
Lower skin	Axial fibre	Tension

*for single span deck in flexural state.

AS 1720.1−1997 and EC5 guidelines disagree on the determination of stresses in the sheathing. From the theory of the stress distribution in SSP skin, AS 1720.1−1997 may be inaccurate whereas EC5 approach appear to be more correct. The validity of the EC5 methodology has also been observed in the laboratory experiments of the subject research. Therefore in order to design SSP systems safely, it is recommended that AS 1720.1−1997 be amended in compliance with EC5 guidelines.

4.4 *Serviceability aspects*

Deflection limits and vibration behaviour form the serviceability requirements for the design of floor systems. They intend to confirm that the structure meets the user expectancies of aesthetics and comfort. Estimating the first aspect is straightforward but assessing the second one can prove more difficult because of the multitude of parameters that need to be considered and the unknowns surrounding SSP systems. Glued interlayers may cause an incremental increase of the natural frequency that could lead to the floor structure to vibrate like a membrane (Polensek 1971).

For the deflection, many codes such as AS/NZS 1170.0:2002 (Australian/New Zealand Standard™ 2002) impose maximum deflection — instantaneous and/or long-term (12a, b) — at mid-span and the limit is often expressed by ratios of the span.

$$u_{inst} = \frac{L}{d_{inst}} \qquad u_{long} = \frac{L}{d_{long}} \qquad (12a, b)$$

where u = deflection [mm] (inst: instantaneous, long: long-term), L = span [mm], d = limitation coefficient.

For the vibration, deflection under a concentrate point load at mid-span and the natural frequency are good indicators of the vibration serviceability of SSP floors. AS/NZS 1170.0:2002 proposes that floor structures should not experience vibration problems if the criterion ─ mid-span deflection between 1.0 to 2.0mm under 1.0kN point load at mid-span ─ is satisfied. If the criterion is denied, a thorough analysis is recommended. EC5 gives a procedure for floors with a fundamental frequency higher than eight Hz, and requirements to satisfy. For floors with smaller fundamental frequency, EC5 requires a special investigation.

5 CONCLUSION

In SSP systems, the sheathing and joists act compositely together. Therefore compared to conventional floor systems, in which the floor members are connected with mechanical fasteners, the section modulus and the stiffness become higher. In addition, the material strength properties of the panels are used more efficiently and the composite and two-way actions are enhanced.

This paper outlines an amendment proposal to Section 5 of the present edition of the Australian code for timber design, AS 1720.1−1997. In the current requirements, the approximation of the tributary width of the sheathing is ignored, and stress verification disagrees with the actual stresses encountered in the skin(s). The procedure found in EC5 is uncomplicated and gives safe design for SSP floors with the most common dimensions. The tributary is estimated with simple formulae, which consider the material of the sheathing and the span of the floor and account for shear lag and/or plate buckling. By imposing normal stress verifications to the sheathing, EC5 considers a stress distribution, which reflects SSP behaviour more accurately. Using the EC5 method for predicting the responses of the specimens of the subject research, reasonable agreement has been observed between the predictions and the test results. Therefore, a design method based on EC5 procedure, with some adaptation to meet Australian particularities (material factors c_{SL} and c_{PB}), will provide the engineers with thorough and reliable design guidelines for SSP systems.

6 ACKNOWLEDGEMENTS

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