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Modelling the stressed skin effect by using shell elements with meta-material model

***S. Pajunen*[a*]*, J. Hautala*[a]*, M. Heinisuo*[b]**
[a] *Tampere University, Tampere, Finland*
[b] *Sorvimo Optimointipalvelut Oy, Tampere, Finland*
** E-mail: sami.pajunen@tuni.fi*

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Abstract. It is a well-known fact that the so-called stressed skin design results in ca. 10–20 % mass and cost savings in a typical steel hall structures. The potential of this design method is however, too often disregarded due to e.g. rather complex and limited existing design rules and instructions. In this paper, a method for determination of generalized elastic parameters is proposed, so that the stressed skin can be modelled in the general finite element software using existing elements and material parameters. With the proposed method, structural designer can take advantage of the stressed skin design in the context of basic design tools as Autodesk Robot or RFEM.

1. Introduction

The stressed skin design fundamentals were established in Europe in the 1970s [1] as described in the comprehensive state-of-the-art review [2]. However, earlier applications were presented in which the bending panels were also carrying axial loads, see e.g. [3]. The stressed skin design method is based on the load-carrying capacity of wall or roof cladding which is typically built of either profiled sheets or cassettes and fastened to a steel frame. When adopted for roofs, the stressed skin action reduces the stresses in columns by transferring the horizontal loads to the gable end walls. In such applications, material cost savings due to stressed skin action is typically 10–20 %, but even higher cost reductions are reported as in [4, 5] and in [6] by adopting simulations and tests, respectively. The design method relies on remarkable way to various empirically obtained parameter values, which are then used to define the flexibility and load-carrying capacity of the designed structural system.

The stressed skin design method is prescribed in an ECCS TC7 report [7] dated to the mid 1990s. The design approach presented in the report is based on the research work established in [8]. A simpler approach for the stressed skin design is also presented, see e.g. [9]. Different aspect of these two approaches are discussed in [10]. The report [7] provides the design method itself, but also some generic rules for fastener and sheet flexibility and capacity calculations. The report does not, however, take into account all the aspects of the stressed skin design as pointed out in [2] and e.g. in [11]. Also the material and structural development would result in modified test results compared to those adopted in [7]. In order to make it possible to broaden the applicability area of the stressed skin design, comprehensive test series were carried out giving more information on non-standard structural cladding systems [12, 13].

The design principles for the stressed skin method are presented in detail e.g. in [8, 14, 15]. The design method ensures that the actual shear force acting in the sheet is less than the capacity of the structure taking into account seam shear force capacities and instability loads for local and global buckling as well as the end collapse. Fasteners are in the central role when defining the capacity and flexibility of the structure. The fasteners are used to connect sheets to each other and sheets to purlins, rafters and end gables as highlighted in Figure 1. In a typical well-designed case, the seam fastener capacity and profile's ability to restrain the

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distortion are the determining factors. The stressed skin action can be taken into account for corrugated sheet as well as cassette and sandwich panels. In the abovementioned conventional stressed skin design approach, the most severe drawback is, that the design rules [7] cannot be implemented to existing design modelling software as such, but they must be taken into account as separate calculations making the stressed skin design process complex and unattractive.

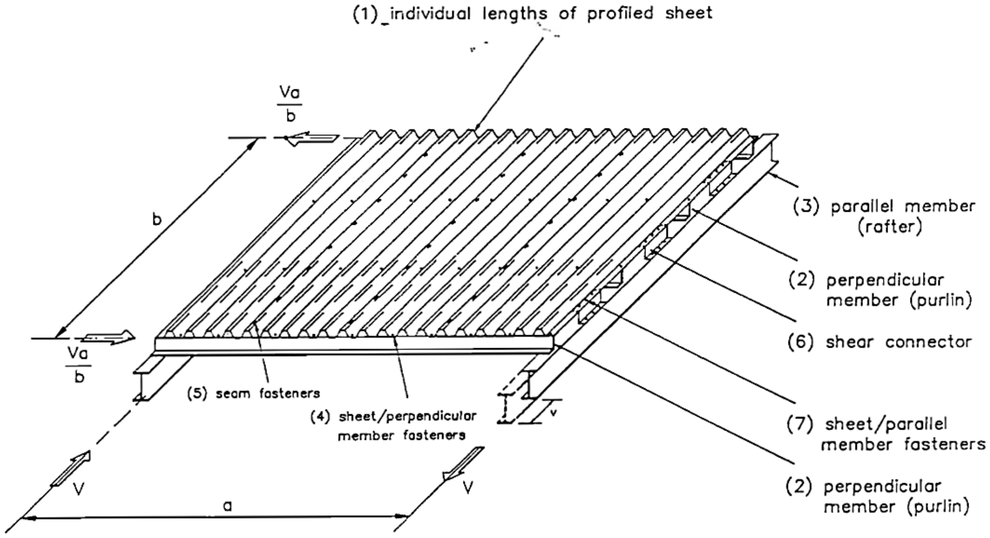

Figure 1. Typical shear panel according to [7].

This paper provides a simulation-driven point-of-view to the stressed skin design. The aim of the paper is to define an equivalent system of finite elements that can be used for the profiled sheet analysis and design instead of modelling the profiled sheet as complex folded plate. The paper discusses which generalized material parameters are needed for the system of elements. The FE-simulations and material definitions in this paper are carried out by using ANSYS, but a similar procedure can be derived for other platforms as well. The main benefits of the method is, that it provides an accurate and computationally efficient way to calculate shear force distribution in the sheet as well as the associated fastener forces.

The paper is organized in a way that the stressed skin principles are revisited in Chapter 2. The procedure for the generation of the proposed method is derived in Chapter 3 and the method usage is explained in detail in Chapter 4. Chapter 5 contains conclusions and further open research questions.

2. Methods

2.1. Stressed skin design principles

The stressed skin approach can be clarified by considering the frame structure augmented with a corrugated steel roof cladding depicted in Figure 2. When the roof is assumed to act as a diaphragm, it transverses part of the lateral load to foundations via shear stresses in the roof skin and via the diagonal bracing located to the end of the building. The roof is divided into shear panels and the stiffness and the shear capacity of each panel is defined according to the cladding and fastening by following the general rules given in [7]. Table 1 presents the ingredients from which the shear panel flexibility is calculated according to ECCS rules [7].

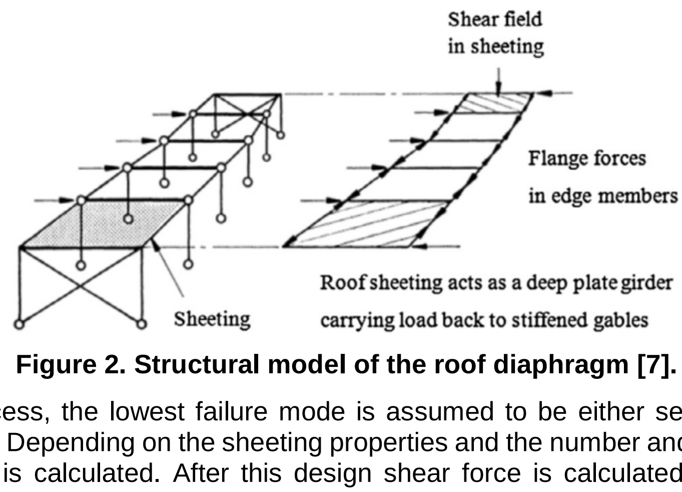

Figure 2. Structural model of the roof diaphragm [7].

In the design process, the lowest failure mode is assumed to be either seam/seam shear failure or seam/rafter shear failure. Depending on the sheeting properties and the number and the type of fasteners, the lower seam failure load is calculated. After this design shear force is calculated, the other failure modes associated with local and global shear buckling as well as profile sheet end distortion are checked. In a case where these instability phenomena become critical before the design shear load, the structure is modified. Otherwise the actual shear force is checked to be below the design shear load.

Being a rather simple design method, the stressed skin design approach is still not used too widely. The main reason for that is possibly the lack of knowledge of the method and the lack of easy-to-use stressed skin design tools. Moreover, the general design guide [7] contains many simplifications that reduce the full potential of the approach.

In order to get the method into more wide use, the finite element analysis and the stressed skin approach should be combined more closely and in a rather general way. That would enable the designer to get accurate distinct connector shear forces and a more realistic shear flow distribution field. Similarly, the actual failure mode could be identified, and its safety margin could be computed against both the true shear forces and the design seam shear capacities.

Table 1. An example of shear panel flexibility determination according to [7]. See the reference for detailed description of the components and other cases.

Shear flexibility due to:		shear flexibility mm/kN
sheet deformation	profile distortion	$c_{1.1}=\dfrac{ad^{2.5}\alpha_5 K}{Et^{2.5}b^2}$
	shear strain	$c_{1.2}=\dfrac{2a\left(1+v\right)\left(1+\dfrac{2h}{d}\right)}{Etb}$
fastener deformation	sheet to perpendicular member fastener	$c_{2.1}=\dfrac{2as_p p}{b^2}$
	seam fastener	$c_{2.2}=\dfrac{s_s s_p\left(n_{sh}-1\right)}{n_s s_p+\beta_1 s_s}$
	connections to edge members	$c_{2.3}=\dfrac{2s_{sc}}{n_{sc}}$
Total flexibility in true shear		$c'=\dfrac{b^2}{a^2}\left(c_{1.1}+c_{1.2}+c_{2.1}+c_{2.2}+c_{2.3}\right)$

2.2. Proposed method

By augmenting the finite element structural model with the stressed skin design principles, the designer can take into account the stiffening effect of the shear panels for arbitrary shaped roof structures. The finite element method can be undoubtedly used to model the actual shear panel and its connections to adjacent structures as Figure 4 depicts. The modelling and accuracy issues of such an approach are discussed in [16]. However, such an accurate modelling is not efficient due to extremely high number of degrees of freedom. Another, rather opposite, approach for taking into account the stressed skin effects is to model the structure using simple models as in [7], in which the Timoshenko beam theory is adopted for modelling the building roof with sheeting. Between these accurate but impractical and computationally inexpensive but inaccurate methods an intermediate numerical method is proposed. The proposed method is based on an assumption that the shear panel flexibility can be expressed as a sum of the sheet flexibility and the flexibility of the associated connections (sheet/rafter, sheet/edge beam, sheet/sheet). The connection flexibility includes the fastener flexibility as well as the flexibility of the surrounding sheet that can undergo buckling and yielding. The aforementioned flexibilities should be taken from test data. In this paper, such test data is not available and FE-modelling is used instead to get the required flexibilities for demonstrating purposes. The method can be implemented into the finite element method so that the sheet stiffness can be taken into account by using orthotropic material model with membrane element, and the connection stiffness's can be modelled as spring elements as depicted in Figure 3. With the proposed method, the stressed skin effect can be effectively implemented to existing structural model.

As mentioned earlier, the loading tests would be optimal way to obtain the flexibility data required by the method. Such data being unavailable, a global model with periodic boundary conditions depicted in Figure 5 is used to define the stiffness of the panel itself including the sheet-to-sheet seam fastener stiffnesses. In the model, periodic boundary conditions for both in-plane directions ensure that no boundary effects are mixed into the sheet stiffness. The FE-model depicted in Figure 5 is subjected to in-plane tensile unit load cases and to an in-plane shear unit load case as illustrated in Figure 6. Based on the deflections due to unit loads, the stiffness of the sheet including the stiffness of the sheet-to-sheet seams is obtained.

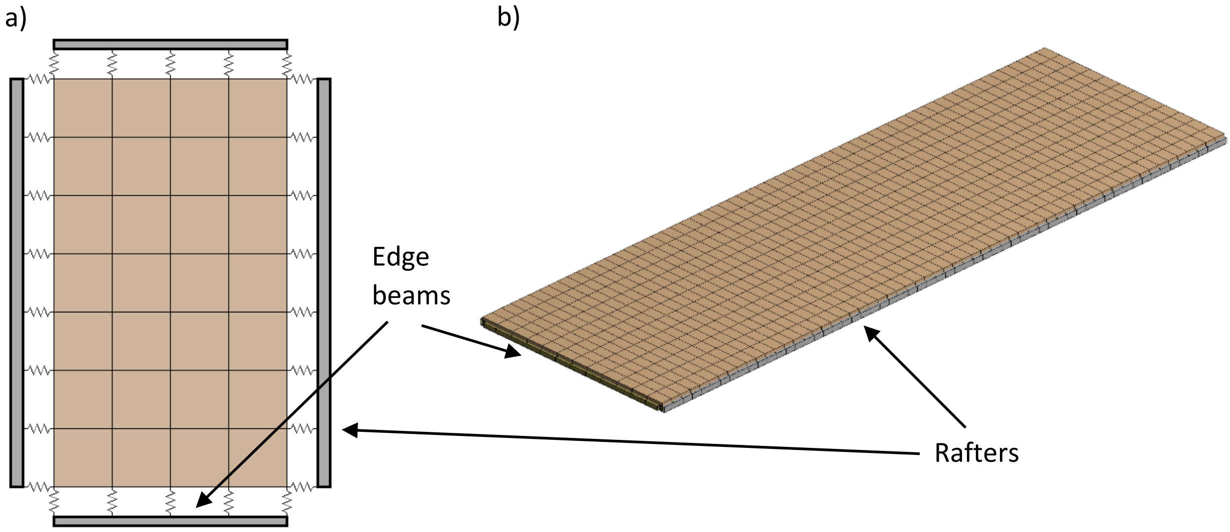

Figure 3. a) Schematic picture on the plate and adjacent rafters and end beams connected with fasteners and b) a simplified flat plate FE-model (counterpart of the accurate model depicted in Figure 4). Typical model 20m* 6m contains ca. 8000 degrees of freedom.

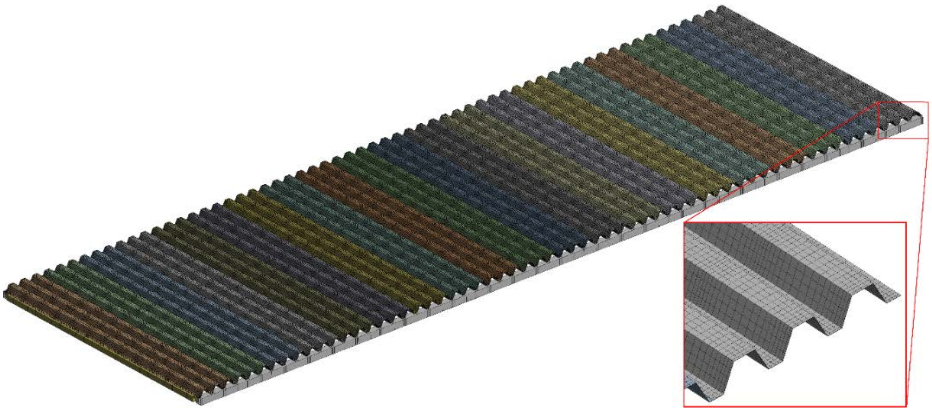

Figure 4. A FE-model of a corrugated sheet panel with accurate geometry modelling. Typical model 20m* 6m contains ca. 4 million degrees of freedom. Each sheet is highlighted by different colors.

Similarly, local FE-models are used to define the in-plane stiffness of the panel connection to the adjacent structures such as rafters, edge beams and end gables. An example of such a FE-model is shown in Figure 7 in which the connection between the sheet and rafter is modelled. In the FE-model, quadratic solid elements (SOLID186 in ANSYS) are used for the sheet and the rafter with two elements in through-the-thickness direction. Linear isotropic material model (E = 200 GPa, ν = 0.3) is used for the steel. The fastener connecting the sheet and the rafter is modelled also with the same quadratic solid elements with dense mesh. Exact geometry of the sheet profile is given in [21]. It should be noted, that the stiffness of the connection is dependent on the fastener stiffness itself but also on the sheet behavior in the vicinity of the connection. Again, such information could be also derived from tests and provided by the manufacturer. However, as discussed in [17], the fastener stiffness is of primary importance when the diaphragm action is taken into account and even multiple testing of the fastener provides no unique results. Thus, the adopting of the finite element method to the fastening modelling is also well-reasoned.

After the structural stiffnesses are defined for the panel and the connections, the corrugated sheet can be modelled as a simplified membrane with transversely isotropic material properties [18] according to

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix} = \frac{1}{1-\nu_{xy}\nu_{yx}} \begin{bmatrix} E_x & \nu_{yx}E_x & 0 \\ \nu_{xy}E_y & E_y & 0 \\ 0 & 0 & G_{xy}(1-\nu_{xy}\nu_{yx}) \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ 2\varepsilon_{xy} \end{bmatrix}. \quad (1)$$

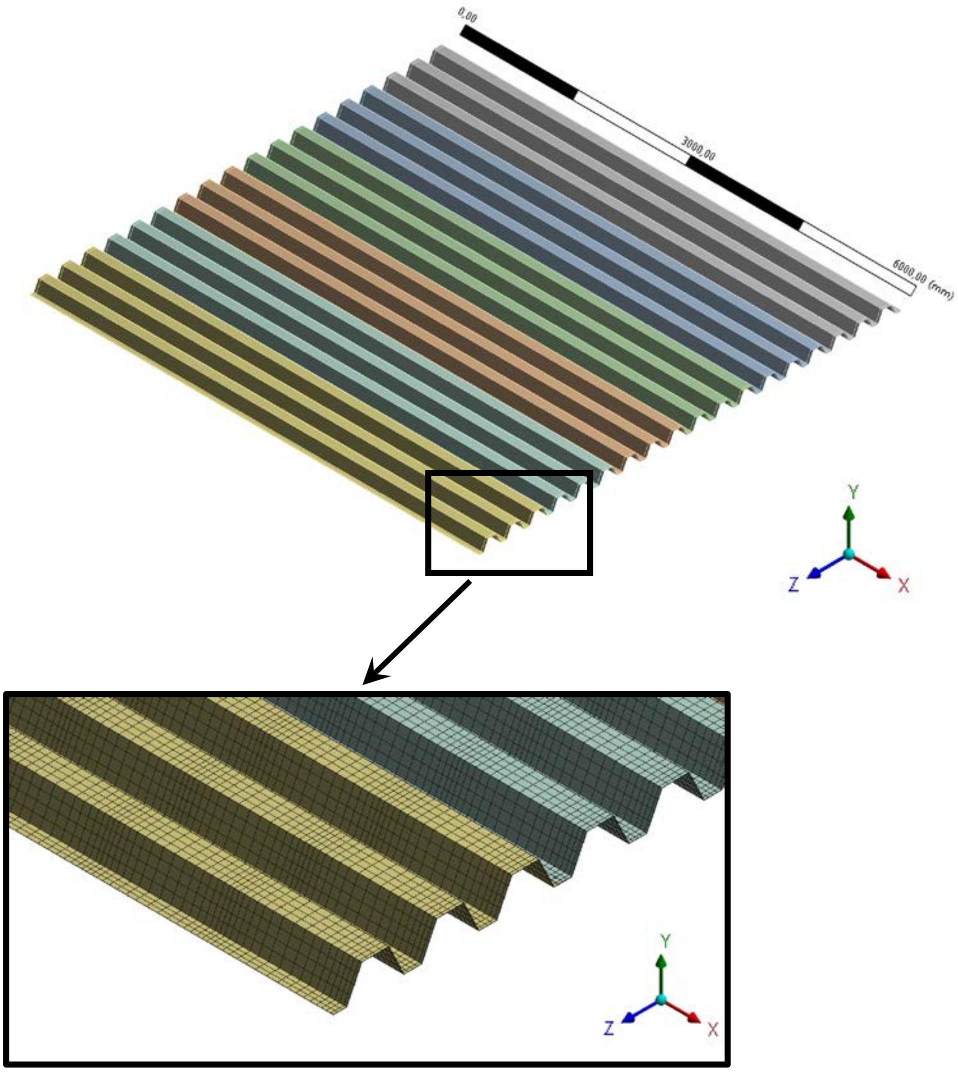

Figure 5. Stiffnesses of the corrugated panel including the sheet-to-sheet seams are obtained from a 6m*6m accurate FE-model with periodic boundary conditions. Sheets connections are included into the model.

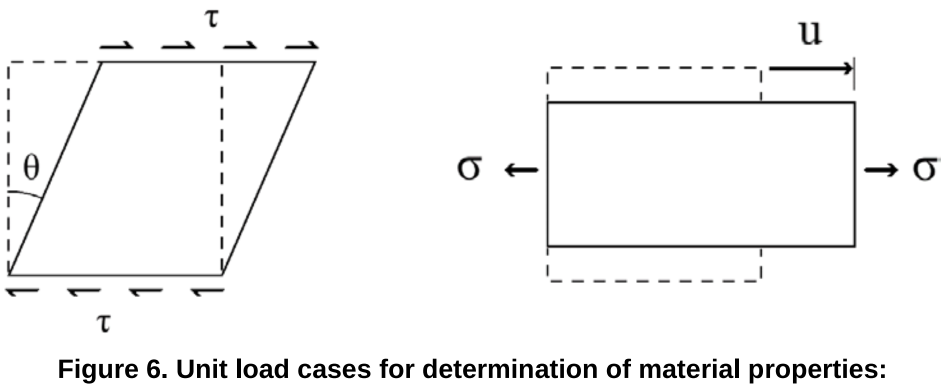

Figure 6. Unit load cases for determination of material properties: Young's moduli E_x, E_y, shear modulus G_{xy}, and Poisson's ratio E_{xy} and E_{yx}.

The membrane is connected to the surrounding skeleton model with joint elements as depicted in the Figure 3, in which four-node linear shell elements (SHELL181 in ANSYS) are used and the grid density in defined according to the fastener intervals. The FE analysis of the flat plate with distinct fasteners itself is trivial and similar simulations are carried out also for wood diaphragms and for hybrid structures in [19] and [20], respectively.

After the steps defined above, the simplified geometry model can be used in any finite element software to model the roof used as stressed skin. The size and shape of the structural entity can be arbitrary. The FE-model of the actual structure gives then results for panel shear forces as well as distinct fastener loads. It should be also noted, that all the previous steps for defining the stiffness's of various parts of the panel structure can be automated. Table 2 highlights the steps of the method.

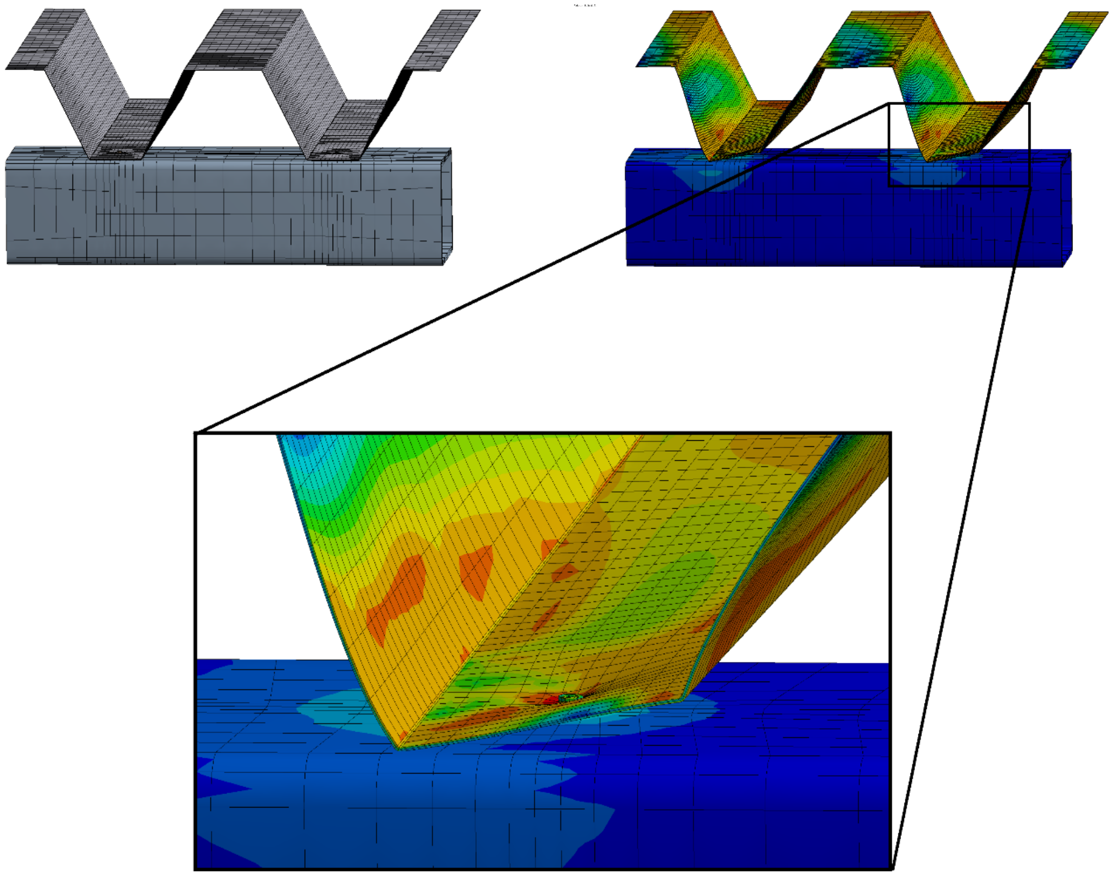

Figure 7. A local finite element model of the sheet-to-rafter connection. Fastening stiffness is influenced by the fastener itself and also by the local deformations of the sheet in the connection neighborhood.

Table 2. Main steps of the proposed method.

Step	Task	Note
#1	Define the sheet structure in-plane tensile and shear stiffnesses. This can be done either by tests or by FE simulations.	Sheet-to-sheet connections can be included in the material model of the sheet or modelled separately as in step #3.
#2	By using FEM, model the shear panel as a flat plate with transversely isotropic material properties defined in step #1	
#3	Define the stiffness for the connections between the sheet and adjacent structures	The stiffness is needed for each sheet/connector pairs
#4	Connect the flat plate into the structural model by using springs with the stiffness defined in step #3	

3. Results and Discussion

The major advantage of the proposed method is that arbitrary sheet panels can be easily attached to an existing skeleton model so that the stressed-skin effect is taken into account for the whole building. As a complementary benefit, the fastener forces are modelled accurately making the joint design more efficient and accurate. The challenges of the method are that the stiffness of each fastener-sheet pair must be defined either by a local FE-model as in this paper or by tests. However, the variety of the mostly used fasteners and sheets is limited making this challenge moderate. When the FE-modelling is used for corrugated sheet structures, numerical problems might appear due to significant difference in normal stiffness's in perpendicular directions. These numerical problems can be however circumvented by using adequate meshing.

In order to highlight the fastener force results, the proposed method is applied to a sheet structure depicted in Figure 8. The same configuration is also analyzed using the ECCS design rules [7] and using the FE-model with accurate geometry model to show the differences in the results. The considered shear panel has the material thickness of 1.0 mm and the total height of 130 mm. The detailed information of the panel can be found from [21]. Sheets are fastened at seams with 4.2 mm diameter screws at intervals of 500 mm. The sheet is attached to rafters (RHS 150×150×8) with 6.3 mm screws from each fold and to edge beams (RHS 120×120×4) with 6.3 mm at intervals of 500 mm.

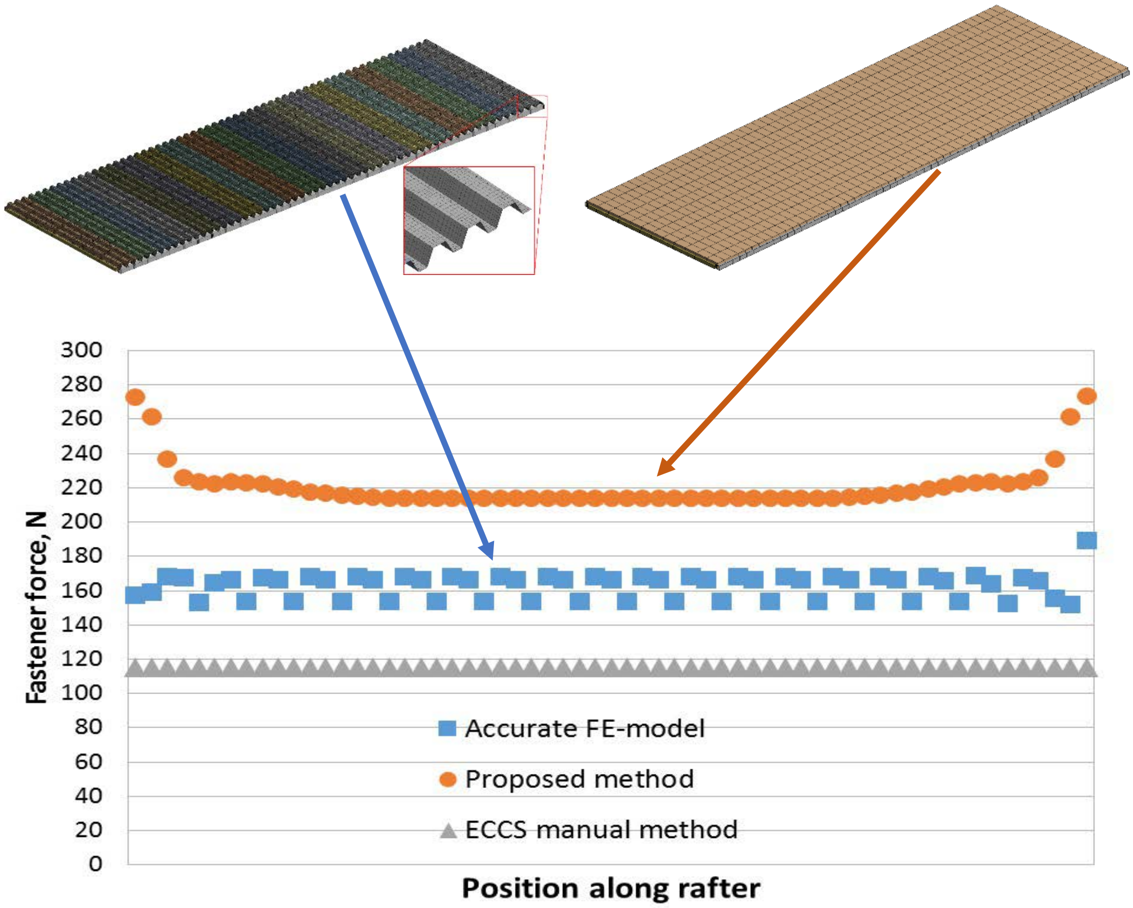

Figure 8. Fastener force distribution at the rafters according to the FE-models and ECCS design rules [7].

The results in the Figure 9 clearly show how the manual calculation according to [7] underestimates the fastener forces as expected due to the conservative nature of the manual design approach. Similarly, the fastener forces according to the proposed method are overestimated as expected. This is due to the general feature of the finite element method, that the structure becomes stiffer when less degrees of freedom are used in the model. However, the small margin between the accurate and simplified model results could be reduced by introducing a certain reduction parameter.

4. Conclusions

In the paper, a new method for the general use of the stressed skin action in the context of finite element modelling is presented. The method uses sheet stiffness's in the in-plane direction and sheet connection stiffness's as input. After defining these values, a simplified flat plate finite element model with transversely isotropic material properties can be used to model accurately any corrugated sheet panel. In this study, ANSYS was used, but any FE-package supporting orthotropic material model could be used, e.g. Autodesk Robot or RFEM. The method presents a potential remarkable competitive advantage to a material producer in a way that the producer can provide the sheet and fastener stiffness values to a FE software developer, after which a FE application could be defined for that product to be used in steel design taking the full advantage on the stressed skin action. The method lies between an accurate FE-modelling and simple hand calculations, as discussed in the Chapter 2. The work required by the method can be done before the actual design process, thus providing an efficient automated design tool.

When applied to corrugated sheet panels, the in-plane tensile structural stiffness's, with different order of magnitude, can produce potential numerical errors in the finite element method when defining the transversely isotropic material properties as discussed in Chapter 3. In the current research, only the in-plane loading is taken into account but in general, also the out-of-plane loading cases can be included into the analysis even if it is not the primary intention of the proposed method. The method is most beneficial when used instead of the conventional Timoshenko beam theory for the structural analysis and used together with the design principles in [7]. The proposed method gives also more accurate results when compared to the method in which the shear panel is modelled as diagonal bar, see e.g. [15]. In a further research, the exact material cost savings of the proposed method compared to the manual design method [7] will be studied. Such research results are needed when evaluating the economical beneficial of the method.

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Contacts:

Sami Pajunen, +358408490571; sami.pajunen@tuni.fi
Janne Hautala, +358505710156; janne.hautala@tuni.fi
Markku Heinisuo, +358405965826; markku.heinisuo@tut.fi

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Моделирование несущих ограждающих конструкций плоскими конечными элементами со свойствами метаматериала

С. Пайюнен[a*], Дж. Хаутала[a], М. Хейнисуо[b]
[a] Технологический университет Тампере, г. Тампере, Финляндия
[b] Sorvimo Optimointipalvelut Oy, г. Тампере, Финляндия
** E-mail: sami.pajunen@tuni.fi*

Ключевые слова: несущая оболочка; диафрагма; профилированный лист.

Аннотация. Как известно, учет несущей способности ограждающих конструкций позволяет на 10–20 % уменьшить металлоемкость и стоимость строительства стальных пролетных сооружений. Тем не менее, преимущества данного подхода часто недооцениваются по причине сложности и ограниченности расчётных норм и рекомендаций. Данная статья предлагает метод определения общих упругих свойств материала, благодаря чему несущая ограждающая конструкция может быть смоделирована в обычном вычислительном комплексе с использованием имеющихся типов конечных элементов и свойств материалов. Данный метод дает возможность инженерам выполнять расчет несущей способности ограждающих конструкций с применением простых вычислительных комплексов, таких как Autodesk Robot или RFEM.

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Контактные данные:

Сами Пайюнен, +358408490571; эл. почта: sami.pajunen@tuni.fi
Джанне Хаутала, +358505710156; эл. почта: janne.hautala@tuni.fi
Маркку Хейнисуо, +358405965826; эл. почта: markku.heinisuo@tut.fi