Optimization of Geometry and Core Materials of Sandwich Panels with Metallic Faces

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Abstract

Due to their numerous advantages, sandwich panels are increasingly used. However, a scientifically sound optimization of sandwich panels has not yet been done. Sandwich producers have made selectively optimization works of their products but mainly with regard to the manufacturing procedures. The aim of the optimization in the current project is an adjustment of the geometry of metal faces together with the properties of the core material in such a way that the load bearing capacity and the costs of sandwich panels are optimal. The production technology should be considered as well. This topic is very extensive mainly due to the numerous parameters which determine the load bearing capacity of sandwich panels.

The optimal geometry of the metal sheets and the optimal mechanical properties of the core material have to be developed on the basis of theoretical investigations and checked in following mechanical tests. In the first step the sets of achievable mechanical properties of the used materials are determined. After this, a combination of the mechanical properties and the geometry of the sandwich panels can be created in order to obtain the largest span. In this regard it is important to achieve a high load bearing capacity of the panel and high utilization factors of all mechanical properties at the same time. The conducted investigations demonstrate possibilities for the optimization of sandwich panels. An achievement of larger spans without a significant increase of costs is possible only by changing the core properties. Furthermore, a significant potential for the optimization of the metal sheets was recognised. There is a possibility to diversify both the quality and the geometry of the steel sheets. The numerous parameters which determine the properties of sandwich panels turn the optimization into a complex procedure. Yet, on the other hand, they also provide numerous alternatives in the optimization processes.

Keywords: optimization, sandwich panel, core material, metal face, load bearing capacity

1. Introduction

1.1 Sandwich panel construction

Sandwich panels used in civil engineering consist typically of a thick core with low density between two thin high density faces. The materials can be configured in many possible combinations. For example, for the cover layers thin metal faces, timber based plates or glass fibre reinforced plastics can be used. The insulating core layer in most cases is made of structured foams like polyurethane (PUR), polystyrene (PS) or of mineral wool (MW).

Sandwich panels are used as light-weight roofs and wall claddings in industrial and commercial buildings. Usually the structures are loaded by permanent loads, like self-weight, snow and wind loads. However, additional loads like temperature differences between external and internal metal faces or creep of the core must be taken in account for statical calculations for sandwich panels.

The high load bearing capacity of sandwich panels is the result of a rigid connection between the core material and the cover layers. The bending moment is distributed to the two faces (e.g. for panels with flat faces in the form of axial forces) and the shear loads are borne by the core layer.

The optimization of sandwich panels in respect to the load bearing behaviour means to adjust the mechanical properties of the core material and metal faces in such way that the largest possible spans can be reached. Other important structural properties of sandwich panels (e.g. insulating properties) or the manufacturing conditions should be considered at the same time.

The current optimization was done on sandwich panels with cover layers made of lightly profiled steel sheets and a PUR core. In this case the thickness of the core can be between 40 and 300 mm. The thicknesses of the steel faces vary between 0.4 and 1.0 mm.

1.2 Optimization of sandwich panels with metal faces – necessity and possibilities

Saving money and resources is very important in almost every industry sector. In this sense, application-oriented research has the role to find the optimal exploitation of materials in the manufacturing process. Compared with steel, concrete or timber constructions, sandwich panels are relatively new components. The first applications of sandwich construction were implemented in the seventies of the last century. That is the reason why sandwich constructions were previously not investigated as deeply as the other construction types mentioned above. This is also the reason why no investigations into the optimization of sandwich panels have been done before.

In this paper a possible method for the optimization of sandwich panels in respect to their load bearing capacity is described.

There are two main assumptions concerning the optimization of sandwich panel load bearing. Firstly: all mechanical properties of sandwich panels shall be adjusted in such way that the largest possible spans can be reached. Second: all the mechanical properties shall be maximally exploited. These two assumptions, together with the several statical systems and different possible load cases that possibly occur, turn the optimization of sandwich panels into a complicated process. The several statical systems which can be used, and the different loads that can occur, generate different failure modes as being decisive for the determination of the span widths.

According to the sandwich theory, the calculation method for sandwich panels shapes the background for the optimization calculations. In this respect the following main properties of sandwich structures describe the load bearing behaviour. These are the crucial factors in the calculation method:

- Wrinkling stress of the metal face σ_w
- Compressive strength of the core f_{Cc}
- Shear strength of the core f_{Cv}
- Young modulus of the core E_C
- Shear modulus of the core G_C

Additionally the shear strength and shear modulus at high temperature and the shear strength for long term behaviour can be expressed as a function of the adequate main values, which were measured at room temperature.

For a determination of these properties, experimental tests on each panel type have to be done. The exact relations between the several mechanical properties are not known. Furthermore, there are no constitutive equations that describe how the achievable wrinkling stress of the metal face depends on the properties of the used materials and the face geometry. It makes the determination of the load bearing capacity only in an analytical way (without tests) to an impossible process. The achievable wrinkling stress of sandwich panels depends on many parameters. These are not only the used materials with defined properties. A very important point is the bond between the core layer and the cover sheets, which can be influenced by many factors. For example the production procedures or the adhesive that is used in the case of adhesively bonded panels can be crucial for the final properties of each single panel type.

To undertake an optimization of sandwich panels by the way of an investigation, a theoretical model for describing the achievable wrinkling stress should be made. In this model the mechanical material properties of the core and also the geometry and the mechanical properties of the metallic faces have to be considered. Because of the existing material and production imperfections the theoretical model can be used only for an estimation of wrinkling stress values.

Because of numerous different factors, which impact the mechanical behaviour of sandwich panels and additionally because of the lack of constitutive equations describing the behaviour, the existing mathematical optimization methods cannot be rationally used at the moment. As an approach, in the first step a parameter analysis according to the calculation method for sandwich panels shall be done.

The aim of the current project is the development of an optimization method that will consider both the core material and the geometry of the faces in only one step. However, due to the mentioned technical hitches, the optimization of sandwich panels will be split into the two steps of an optimization of the core and an optimization of the metallic faces.

2. Optimization of core materials

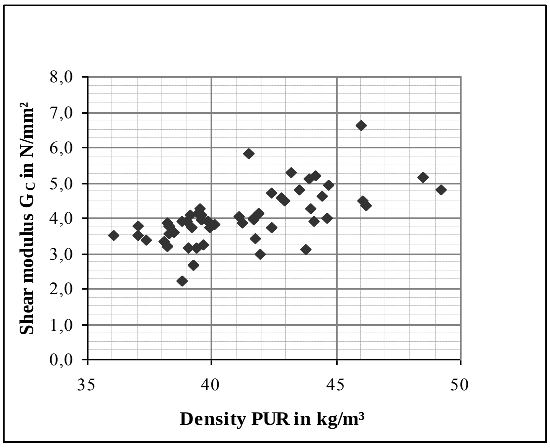
2.1 Theoretical pre-analysis into optimization of core materials

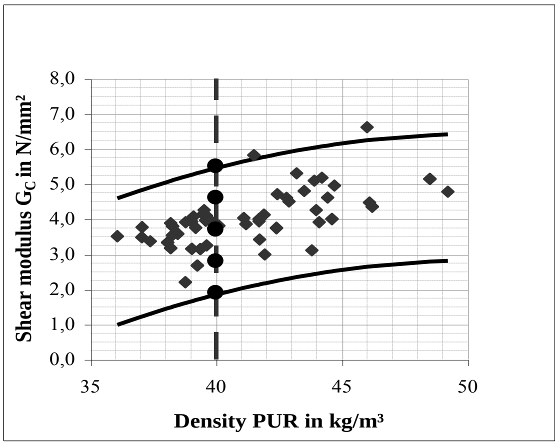
In this paper the investigation into optimization of one of the mostly used core materials – polyurethane – will be shown. The optimization of the core material means to define the mechanical values – the strengths and the modulus (like in 1.2) – which are needed for getting an optimal core material.

In the first step it is possible to execute the optimization of core materials for existing panel geometries. In this case any existing panel with a given geometry can be taken and the mechanical properties of the core can be optimized in such a way that the given geometry and the new core material bring an optimal panel regarding to the load bearing capacity.

The mechanical properties are included in certain sets. In this case the optimization of core material means to search for combinations of mechanical properties from defined sets. The created combinations should lead to a high load bearing capacity of the panel and maximal utilization factors of all mechanical properties by limitation of the spans. First of all the sets of mechanical properties of core material (PUR) were determined according to known material properties. The background for this procedure is that the material combinations should be set up of material properties which are possible to manufacture.

For instance the shear modulus depending on the density of the core material is shown in Figure 1a. After all relevant mechanical properties were collocated in this way the boundaries for achievable mechanical properties of the core were defined (see Figure 1b). Depending on the chosen density, the possible scope of mechanical properties is known and the raster for creation of new combinations can be defined. In this case a raster of five values was chosen.





a) b)

Figure 1a: Values of shear modulus of PUR depending on the core density; Figure 1b: Example for taken value raster for creating the combinations of core properties, density of PUR 40 kg/m³;

The known scopes for all relevant mechanical values can be determined:

PUR, Density 40 kg/m³

G_C ⟨1,9; 5,5⟩ in N/mm²

E_C ⟨1,0; 5,0⟩ in N/mm²

f_{Cc} ⟨0,060; 0,200⟩ in N/mm²

f_{Cv} ⟨0,085; 0,225⟩ in N/mm²

For creating the properties combinations for all values scopes a raster of five was chosen

Table 1: Creation of combinations of mechanical core properties for PUR, density 40 kg/m³

$G_{C,\,T=20°C}$	$G_{C,T>20°C}$	$f_{Cv,T=20°C}$	$f_{Cv,T>20°C}$	$f_{Cv,t=\infty}$	f_{Cc}	$E_{C,T=20°C}$
in N/mm²	*in N/mm²*	*in N/mm²*	*in N/mm²*	*in N/mm²*	*in N/mm²*	*in N/mm²*
1,9	*1,7*	*0,085*	*0,077*	*0,038*	*0,060*	*1,0*
2,8	*2,5*	*0,120*	*0,108*	*0,054*	*0,095*	*2,0*
3,7	*3,3*	*0,155*	*0,140*	*0,070*	*0,130*	*3,0*
4,6	*4,1*	*0,190*	*0,171*	*0,086*	*0,017*	*4,0*
5,5	*4,9*	*0,225*	*0,203*	*0,101*	*0,200*	*5,0*

The combination of the main values (marked columns in Table 1) gives 625 compositions of mechanical properties.

625 sandwich panels with the same face geometry and different core materials were generated. By determination of the spans for all 625 fictive panels one of them can result as optimal. The optimal panel should give the largest span and the mechanical properties of the core should be exploited maximal.

Example:
Sandwich panel with given geometry of faces and a PUR core;
Core density 40 kg/m³
Thickness of the panel D = 80 mm
External face, steel, micro lined profile, t_{F1} = 0,60 mm;
Interior face, steel, lined profile, t_{F2}= 0,50 mm;

Statical system:
Vertical wall panel, one–span beam

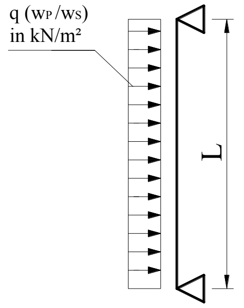


Table 2: Mechanical properties of the core; basic panel and optimal combination

Element	$G_{C,T=20°C}$	$G_{C,T>20°C}$	$f_{Cv,T=20°C}$	$f_{Cv,T>20°C}$	$f_{Cv,t=\infty}$	f_{Cc}	$E_{C,T=20°C}$
	in N/mm²	*in N/mm²*	*in N/mm²*	*in N/mm²*	*in N/mm²*	*in N/mm²*	*in N/mm²*
Basic element	*3,6*	*3,6*	*0,110*	*0,110*	*0,050*	*0,100*	*3,7*
Optimal core material	*5,5*	*5,0*	*0,189*	*0,170*	*0,085*	*Depend on support width*	*5,0*

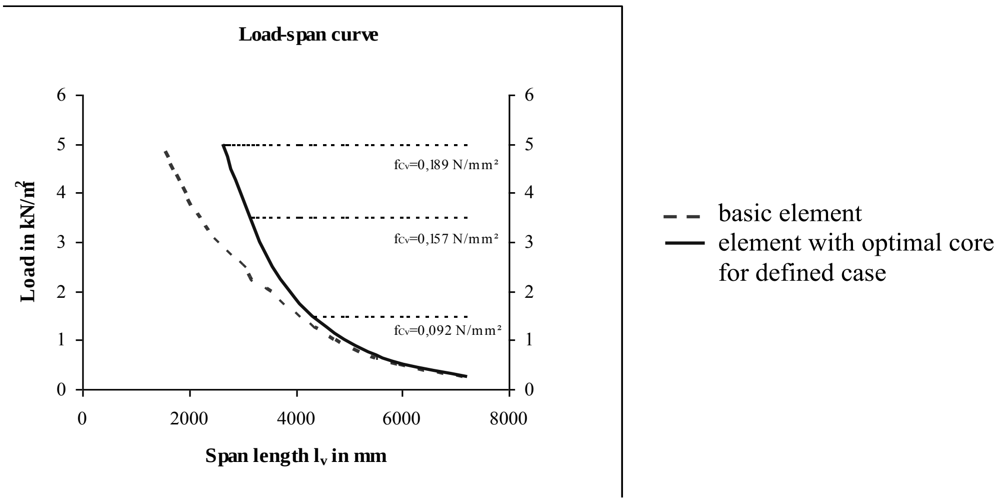


Figure 2: Load-span curve, example for basic panel with given core and a panel with optimal core

As a means to simplify the analysis of the calculations results, the achievable spans were shown in dependency on the increasing loads, like in Davies (2001), see Figure 2.

The results of the investigations show that the increase of the span is possible even only due to an improvement of the core properties. But in the most relevant cases the wrinkling stress or the deflection limitation are decisive for the determination of the span of sandwich panel. This can be observed in the area of low load (between 0,25 and 1,5 kN/m²).

The wrinkling stress depends on the core material, but even more on the properties of the metal faces. That is the reason for a deeper investigation into optimization of the geometry of metallic faces in respect to getting higher wrinkling stress.

3. Optimization of lightly profiled metallic faces

3.1 Background

The optimization of metallic faces means to adjust the geometry and the quality of the metal face in such a way that the achievable wrinkling stress of the face will be maximal. Many types and forms of metal faces ... ements and strongly pr... only. The optimizatio...

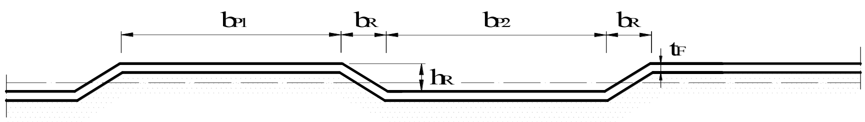


Figure 3: L...

During the ... ation it was observed th... s. It can be supposed th... connection between the ... h influence have other ... achievable wrinkling stress? Beside the influence of the geometry the elastic bedding on the core through its mechanical properties should be considered as well.

The influence of the geometry of metal sheets on the achievable wrinkling stress was done both in theoretical investigations and experimental tests.

3.2 Theoretical pre-analysis into optimization of metal faces

At the moment in optional calculation of wrinkling stress, the lightly profiled faces are regarded as flat faces. In this way their explicit higher load capacity is not regarded. To achieve an optimization of the geometry, a new analytical model for an assessment of the wrinkling stress of lightly profiled faces depending on the geometry of the profiling was compiled. The model is based on the existing theories by Plantema (1966) and Stamm/Witte (1974).

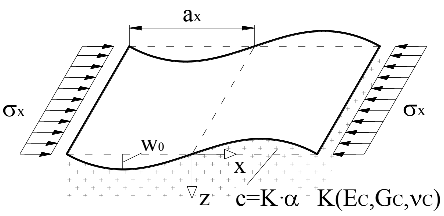


Figure 4: Stresses and deformation on flat, constantly bedded sandwich panel structure

To the differential equation for flat plates a term for consideration of the bedding of the core was added.

$$B_F \cdot (w'''' + 2 \cdot w''^{\cdot\cdot} + w^{\cdot\cdot\cdot\cdot}) + F_x \cdot w'' + F_y \cdot w^{\cdot\cdot} + F_{xy} \cdot w'^{\cdot} + c \cdot w = 0 \qquad (1)$$

Where $B_F = \dfrac{1 \cdot t_F^3}{12 \cdot (1 - \nu_F^2)}$ stiffness of the plate (2)

t_F, ν_F thickness and Poisson ratio of the face

$c = \alpha_x \cdot K$ rigidity constant of the bedding (3)

By consideration of the behaviour conditions, like deformation of flat plate on elastic bedding and the failure mechanism, the differential equation can be reduced to the searched axial force in the plate:

$$F_x = B_F \cdot \alpha_x^2 + \frac{c}{\alpha_x^2} \qquad (4)$$

where c like in (3),

$\alpha_x = \dfrac{\pi}{a_x}$ is the half cycle rate in longitudinal direction (5)

and $K = \dfrac{2 \cdot (1 - \nu_C)}{(1 + \nu_C) \cdot (3 - 4 \cdot \nu_C)} \cdot E_C$ is the bedding constant (6)

where ν_C is the Poisson ratio of the core.

For consideration of the shear modulus in the elastic bedding due to the core, the relation between shear modulus and young modulus for isotropic material was used

$$E_C = 2 \cdot (1 + \nu_C) \cdot G_C \tag{7}$$

and the bedding constant was transformed to

$$K = \frac{2 \cdot (1 - \nu_C)}{(3 - 4 \cdot \nu_C)} \cdot \sqrt{\frac{2 \cdot G_C \cdot E_C}{(1 + \nu_C)}} \tag{6a}$$

Inserting the rigidity constant of the bedding in (4) gives

$$F_x = B_F \cdot \alpha_x^2 + \frac{K}{\alpha_x} \tag{8}$$

The lowest value for F_x is the buckling load of the flat plate F_{ki}:

$$\frac{dF_{ki}}{d\alpha_x} = 0 \tag{9}$$

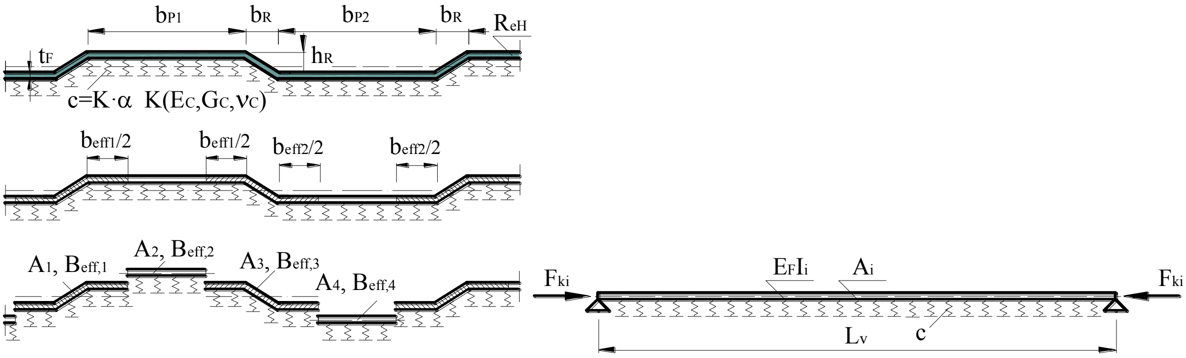
$$F_{ki} = \frac{3}{2} \cdot \sqrt[3]{2 \cdot K^2 \cdot B_F} \tag{10}$$

In the case of a lightly profiled face, the failure mechanism is similar to a flat face. Nevertheless, the ribs should be additionally considered as stiffeners. For this reason the lightly profiled face was divided in the areas of stiffeners (ribs with effective widths of plates[1]) and flat plates between stiffeners like in Figure 5. The lightly profiled face is considered as a configuration of beams and flat strips on elastic bedding.

The buckling load for each beam with the partial cross sections like in Figure 5 can be taken like in (10):

$$F_{ki,i} = \frac{3}{2} \cdot \sqrt[3]{2 \cdot K^2 \cdot B_i} \tag{11}$$

[1] Effective widths of plates were determined according to DIN 18807-1, 1987-06



$$\sigma_{w,i} = \frac{F_{ki,i}}{A_i} \tag{12}$$

$$\sigma_{w,i} = \frac{3}{2t_D} \cdot \sqrt[3]{2 \cdot K^2 \cdot B_{eff,i}} \tag{13}$$

and $\sigma_{w,i} \leq R_{eH}$

The partial wrinkling stresses were spread in the complete cross-section area and the total wrinkling stress of a lightly profiled ribbed face is:

$$\sigma_w = \frac{\sum \sigma_{w,i} \cdot A_i}{A_i} \tag{14}$$

3.3 Testing of panels with lightly profiled faces

For investigation of the influence of the depth of ribs by lightly profiled faces on the bending moment capacity full scale tests on simply supported panels were done. The tests were made according to EN 14509 (2006), A.5. Sandwich panels with steel faces and a core of PUR were tested. The specimens were taken from one production batch. This provided the possibility to keep all parameters constant. Only the depth of the ribs was varied.

$b_1 = b_2 = 50$ mm, $b_R = 2{,}65$ mm; $t_F = 0{,}60$ mm

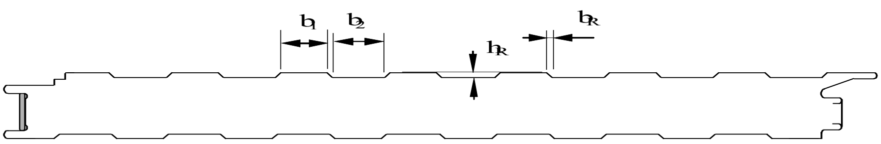


Figure 6: Test specimen; ribbed profile

Table 3: Test results for specimens with varied depth of the ribs

Type of panel	*Nominal thickness of panel*	*Tested face geometry*	*Depth of the ribs*	*Wrinkling stress*	*Increasing of wrinkling stress by varied depth of the ribs*
Wall	*d = 80 mm*	*1.1. Ribbed profile*	$h_R = 0{,}63$ *mm*	*170,4 N/mm²*	-
	d = 80 mm	*1.2. Ribbed profile*	$h_R = 0{,}90$ *mm*	*188,5 N/mm²*	*10,6 %*
	d = 80 mm	*1.3. Ribbed profile*	$h_R = 1{,}26$ *mm*	*208,2 N/mm²*	*22,2 %*

According to the test results the achievable wrinkling stresses (average values) of the metal faces were determined. The results show a clear connection between the depth of the ribs by lightly profiled metal faces and the achievable wrinkling stress. There is the possibility to increase the wrinkling stress considerably by insignificantly deepening the profiling. With regard to the optimization processes is it important that the increasing of the wrinkling stress is possible even by using the same mass of steel and core material.

The wrinkling stress for the tested panels was calculated according to (14). In Figure 7 the calculated wrinkling stresses and the corresponding test results are presented. There is the varied parameter - depth of the ribs - presented on the abscissa and the achievable wrinkling stress values are shown on the ordinate.

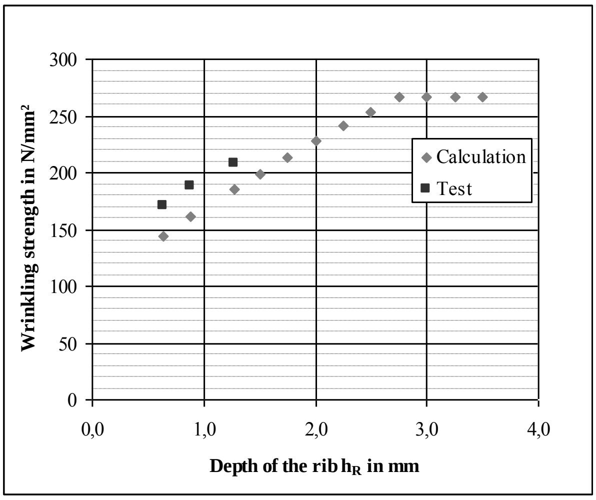


Figure 7: Wrinkling stress depending on the depth of the profiling by ribbed profile

4. Conclusions

A method for optimization of sandwich panels with thin metallic faces in respect to their load bearing behaviour was shown. There is the possibility to optimize both the core material and the geometry of the metallic faces. The connection of those two methods will give a possibility for optimizing sandwich panels in only one step.

It has been found that very often, for the relevant cases of loading, the wrinkling stress or deflection limit is decisive for limitation of the span widths. These two values can not be significantly improved by only changing the core material. For this reason the improvement of the wrinkling stress and the reduction of the available deflection should be taken as important points for optimizing the cover layers.

The changes on the face geometry can lead to a higher wrinkling stress. Additionally the selection of optimal strength and stiffness values of the core material can increase the load bearing capacity.

The numerous factors which influence the mechanical behaviour of sandwich panels provide many options for an improvement of the load bearing capacity. As a practical effect, the producers are able to implement selective changes for getting better load bearing of their products.

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