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Steel Sandwich Panels in Marine Applications

Preliminary communication

Steel sandwich panels welded by laser can offer 30-50 % weight savings compared to the conventional steel structures. *Helsinki University of Technology/Ship Laboratory* has done active research during the past 10 years on various topics related to the laser welded steel sandwich panels. The work carried out includes development of design formulations for the ultimate and impact strength, analysis of fatigue strength for the joints, and development of solutions to improve the behaviour under fire. A number of research projects both at the national and European level have been ongoing. In the paper, a summary of the marine applications, main benefits and problem areas of the panels as well as available design tools are given. A case study for weight and cost optimisation of a hoistable cardeck is also presented proving some of the described benefits of all steel sandwich panels.

Keywords: *design optimisation, hoistable cardeck, laser welding, shipbuilding structures, steel sandwich panels*

Primjena čeličnih sendvič panela u brodogradnji

Prethodno priopćenje

Laserski zavareni čelični sendvič paneli mogu pružiti 30-50 % uštede u težini u odnosu na kovencionalne čelične konstrukcije. *Helsinki University of Technology/Ship Laboratory* je tijekom proteklih 10 godina obavio aktivno istraživanje različitih tema vezanih za laserski zavarene čelične sendvič panele. Obavljena istraživanja uključuju razvijanje projektnih formula za maksimalnu i udarnu čvrstoću, analizu zamorne čvrstoće spojeva te razvijanje rješenja u svrhu poboljšanja ponašanja panela izloženog vatri. Postoji niz projekata na nacionalnoj i europskoj razini koji se bave ovom problematikom. U ovom radu daje se sažeti prikaz primjene čeličnih sendvič panela u brodogradnji, njihove osnovne prednosti, problemi vezani uz njihovu primjenu te raspoloživi projektni alati. Prikazana je i analiza slučaja optimiziranja težine i troškova podizive palube za vozila koja potvrđuje neke od opisanih prednosti svih čeličnih sendvič panela.

Ključne riječi: *optimizacija projekta podiziva paluba za vozila, lasersko zavarivanje, brodograđevne konstrukcije, čelični sendvič paneli*

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1 Introduction

Proposals for the construction of sandwich-like components were made in different industrial branches as early as the 1950's. However, the application of laser welding started to be increasingly discussed only after the high power laser sources became available on the market at more affordable prices. Due to its high energy intensity resulting in a low heat input and a deep penetration effect, laser welding offers a number of benefits for the production of all-metal and hybrid-metal sandwich panels. High pre-fabrication accuracy of the components, high welding speed and the possibility to connect internal stiffeners with the face sheets from outside have led to a wide application of laser welding in the construction of metal sandwich panels.

In the 1980s the United States Navy led the development of laser welded sandwich panels with a robot system at the *Navy Joining Centre* at *Pennsylvania State University*. The development resulted in some prototype panels, first strength tests [1], [2], [3] and first limited applications, such as antenna platforms on the US Navy ships [4].

Between the late 1980's and early 90's Europe took over the lead in research related to laser welded sandwich panels. Research was initiated especially in Britain, Germany and Finland. In Britain the strength of spot welded steel sandwich panels was studied by the *School of Civil Engineering* at the *University of Manchester* [5], [6], [7]. They performed both theoretical and experimental investigations on the behaviour of steel sandwich panels under various loading and boundary conditions. Mechanical properties of adhesively bonded steel sandwich panels were investigated in [8] and [9].

A large German project [10] conducted by *Meyer Werft* between 1994 and 1999 investigated both the production and application of sandwich panels in cruise vessels. This led to the development of the I-Core panels [11].

In Finland the research related to all steel sandwich panels was initiated in 1988 in the *Ship Laboratory of Helsinki University of Technology*. The first study focused on the application of sandwich panels in the shell structures of an icebreaker. Since then a considerable number of research projects in Finland, such as Shipyard 2000, Weld 2000 and Kenno – Light Structures

Technology Program, investigated manufacturing, design and design optimisation of steel sandwich panels. This was summarised in [12] and [13].

The European research project SANDWICH [14] joined forces between the main actors in Europe and continued the development based on previous national projects. The project aimed at enlarging the field of applications of sandwich panels in various surface transport sectors, by further improving the sandwich panel properties by implementing local filling material into the panels, developing and validating reliable design formulations within the design tool. One very important outcome of the project were the first *DNV* guidelines for the classification of these panels in marine applications [14].

More recently, another European Coordination Action called SAND.CORe [15] was started with the intention to assess the current status of the development of sandwich panels in general and to elaborate the guidelines of best practice, by compounding the knowledge of 16 experts from 8 European countries.

This paper first gives a summary of some of the studied practical applications and current knowledge related to various design topics of steel sandwich panels. Finally, a more detailed presentation is given of the results of optimisation of a hoistable car deck that applied steel sandwich structure for panelling.

2 Steel sandwich panels: types, benefits and production

Sandwich panels in general can be classified as: composite sandwich and metallic sandwich panels. Composite sandwich panels consist of non-metallic components such as FRP, PU foam etc. and are typically applied as load carrying structures in naval vessels and leisure yachts, and mainly as non-load carrying elements on merchant and large cruise ships. For metallic sandwich panels there are basically two types of panels: panels with metallic face plates and bonded core such as SPS panels and panels with both metallic face plates and core welded together. The metal material can be either regular, high tensile or stainless steel, or aluminium alloys. This paper focuses on steel sandwich panels welded by laser. The steel sandwich panels can be constructed with various types of cores as summarised in Figure 1. The choice of the core depends on the application under consideration. The standard cores such as Z-, tube- and hat-profiles are easier to get and they are typically accurate enough for the demanding laser welding process. The special cores, such as corrugated core (V-type panel) and I-core, need specific equipment for production, but they usually result with the lightest panels. Naturally, during the production process or after welding of faceplates plates and core together, the steel sandwich panels can also be filled with some polymer, mineral or rock wool, concrete etc. to improve the behaviour for specific targets.

All kinds of sandwich panels have a number of common benefits, like good weight to stiffness ratio, high pre-manufacturing accuracy etc. and problems, e.g. integration in a ship structure, while the various variants also show a number of specific advantages and disadvantages. Steel sandwich is relatively light and the total costs are very competitive to other light structures solutions. Typically, normal strength steel is used with steel sandwich panels as buckling or displacement is the dominating failure criteria, therefore high strength steel does not usually give any major benefits. For areas with high demands for corrosion protection or easy maintanence stainless steel can be also applied. Laser welding require relatively high investment costs, therefore the price of the panels is strongly related to the volume of the production. However, as the material costs are smaller due to the decreased weight, typically the price of the steel sandwich panels/unit area is about the same magnitude as that of conventionally stiffened steel panels. Sandwich panels and in particular laser welded sandwich panels offer a number of benefits, such as:

- Good stiffness to weight ratio offering a weight saving potential of up to 50% as compared to traditional stiffened plates;
- Less space consumption and the smaller total height of structure, comprising steel decks and underlying systems like cables, tubes and insulation;
- Good properties regarding heat insulation, noise damping and fire safety, in particular when filling materials or top layers are implemented; weight and man hour consumption of external insulation can be drastically reduced due to the flat surface of the sandwich panels;
- Significantly improved crashworthiness, with filling materials further increasing crashworthiness;
- High pre-manufacturing accuracy and flatness, reducing the amount of fairing and fitting work in outfitting; no need for floor levelling for sandwich structures;
- Competitive prices which are in the same order of magnitude as conventional steel structures (standard steel sandwich panels without filling); fabrication prices can be further

Figure 1 **Various solutions for the core profiles to be applied in steel sandwich panels [16]**
Slika 1 **Različita rješenja profila jezgri koja se mogu primijeniti u čeličnim sendvič panelima [16]**

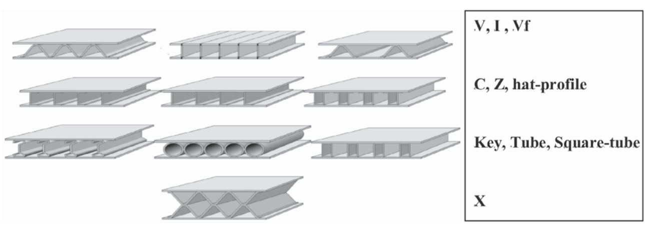
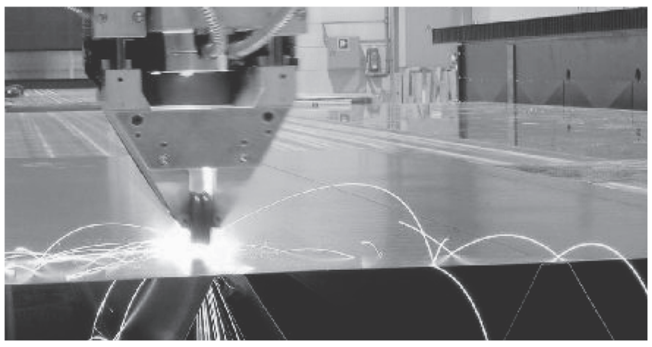


Figure 2 **Laser welding of steel sandwich panels by *Mizar* in Finland [17]**
Slika 2 **Lasersko zavarivanje čeličnih sendvič panela u tvrtki *Mizar* u Finskoj [17]**



decreased with more standard applications, leading to series effects and potentially lower material prices;
- Larger unsupported span and drastic reduction of pillars, leading to more open rooms and more architectural freedom;
- Large variability for design modifications, allowing the tailor made panels for dedicated application cases.

Sandwich panels are pre-fabricated commercially by *Meyer Werft* shipyard in Germany and a couple of Finnish companies: *Mizar* and *Kennotech*. Production in *Mizar* is seen in Figure 2. Also, large steel manufacturers are interested to produce sandwich panels once a critical mass of applications is achieved. *Mizar* has high volume production capabilities with two 8 kW lasers, one 5 kW, and one 12 kW laser. The maximum panel size is 4 m x 17 m, with plate thicknesses reaching up to 6 mm and panel height up to 500 mm.

3 Marine applications

Practical applications of laser welded sandwich panels in shipbuilding were realised from the mid 1990's onwards. After some very limited prototype applications in the US Navy the focus shifted to Europe. The development and application of laser welded sandwich panels in the United States was driven by the US Navy and focused on naval applications. Main reasons for the application were weight savings and increased resistance to fire, blast and penetration.

The development in the US comprised fabrication of sandwich panels by conventional tack welding and laser welding, estimation of sandwich properties such as strength, fire, and blast, some basic investigations on repair and maintenance as well as investigations on some potential applications, the largest being an antenna platform consisting of several *Lascor* panels, i.e. panels with corrugated core. The weight savings were estimated to be as much as 50% [3, 4].

Meyer Werft pioneered the application of laser welded sandwich panels, primarily with webs as internal stiffeners. This product is marketed under the brand name *I-Core*. These had been widely used in cruise ships built at *Meyer Werft*, in inland waterway cruise ships built at *Neptun Industrie* shipyard, as well as in RO-RO decks supplied by *MACOR Neptun*. Also, panels were supplied to other shipyards as well as to other applications outside shipbuilding such as parking houses. Details can be found at the *I-Core* website [11].

First applications in cruise ships by *Meyer Werft* started in 1995, immediately after the first sandwich panels had been produced at the test installation. Applications focused on wing bulkheads and staircase landings, but also for other walls like balcony partitions. Later on, the applications extended to stairs and platforms in the public areas. *Meyer Werft* panels were also applied in two cabin decks on the cruise ship *Superstar Virgo*. This became possible after extensive fatigue tests of the joints between the sandwich panels and surrounding conventional structures. Early applications at cruise ships are described in [18] and various conference papers, e.g. [10].

Sandwich panels proved to be an excellent solution for walls and platforms, offering space savings and high accuracy resulting in a reduced straightening work. Additionally, significant reduction of floor levelling material, ease and reduction of insulation as well as a high degree of pre-outfitting, avoiding "hot works" in block and final assembly, have been experienced. Cut outs and penetrations together with connecting profiles were developed and installed in the panel fabrication workshop. Technologies for last minute modifications as well as repair have been developed and are applied if found necessary. Shipyard personnel have become accustomed with these applications, and no major problems have been recorded in assembly and in operation for almost ten years of service [10, 11].

In Finland, marine applications have seen several prototypes so far, whereas the activities in the building sector have increased rapidly during the past year. The applications for example include upper floor panelling for a sport stadium and rapidly constructed houses using steel sandwich modules. The marine applications mainly relate to bulkheads and staircase landings onboard cruise ships [16].

4 Design characteristics

The basic text books for sandwich structures [19] and [20], give the basic design equations for these types of panels. However, these books concentrate mainly on composite panels. Special design formulations and tools for steel sandwich have been developed in the Finnish national research projects and in the EU-SANDWICH project, the formulations are summarised e.g. in [12]. The developed design formulations support calculations of response, fatigue, fire, corrosion, sound and vibration. Formulations are intended for designers as well as for the use in optimization. One practical case engulfing some of these characteristics is described in the following chapter.

The strength formulations cover the basic first principle design approaches. In these formulations, the effect of possible filling inside the panel, using e.g. balsa, polyurethane or concrete, is included to develop tailor made panels for specific application cases. Design tools such as *ESAComp MSE* [21] are available, although limitedly, which allows a shipyard designer to integrate sandwich structures into a global finite element model of a ship as well as to design optimal panels.

4.1 Calculation of response

The first step in the design process of steel sandwich panels is to find out the best combination of the cross-section scantlings. After the initial scantlings have been set up, one can evaluate the linear elastic response in several different ways. For practical design the methods are mainly: beam theory, orthotropic plate theory and 3D-shell Finite Element (FE) models. In general, beam theory gives acceptable results for the panels with either free longitudinal or transversal edges and with load evenly distributed along the whole width of the sandwich panel. In ship solutions these kinds of cases exists very rarely since the panel is usually supported from all four edges. For more complicated combinations of loads and boundary conditions the orthotropic plate theory considering both bending and shear must be used. However, the closed form solutions exist only for several combinations of load and boundary conditions namely simply supported and clamped plates with uniform pressure or point loads. Usually these solutions are based on the assumption that the panel cross-section is symmetrical about its mid-plane. In addition, it has been shown in [12] and [22] that the distribution of bending moment derived this way is not realistic.

To overcome these limitations Romanoff and Klanac in [23] developed analytical formulations for equivalent Reissner-

Mindlin shell elements to be used for 2D Finite Element Analyses. Stiffness properties were derived analytically for both empty and filled panels with I-, C-, O-, V-, Vf- and Z-core geometries.

4.2 Strength criteria

When the response of the panel is known, the structure can be checked against strength and maximum displacement criteria. The strength criteria include: overall buckling of the panel, local buckling of panel's structural members, faces and web plates, and their maximum tolerable local loads. Local buckling of the panel's structural members can be calculated with good accuracy, with the formulae presented for example in the classification society's rules or handbooks of strength of materials. Figure 3a shows an example of the failure process of corrugated core steel sandwich panels under constant pressure with simply supported edges. The panel dimensions were: length 2500 mm, breadth 340 mm, height 53 mm, face plates 1 mm, web plate 0.7 mm. Yield strength for the face plates was 153 MPa and for the webs 184 MPa [16]. Figure 3b illustrates the middle part of the panel after testing.

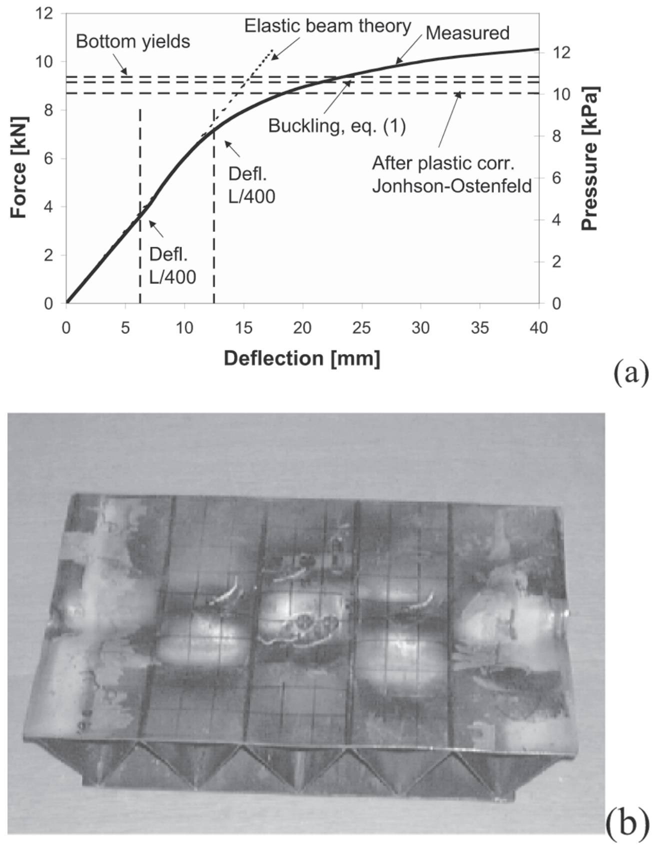


Figure 3 **Force-deflection curve under constant pressure for steel sandwich panel (a) and the middle part of the panel after the testing (b) [16] and [27]**

Slika 3 **Krivulja sila-progib pri konstantnom tlačnom opterećenju za čelični sendvič panel (a) i središnji dio panela nakon testiranja (b) [16] i [27]**

The failure modes, which occur under high local loads, are web plate plastic collapse and denting of the face plate. Both might occur under static or dynamic (impact) loading. For web plate collapse and top plate denting, the derived formulations for foam filled steel sandwich panels under static loading are presented by Romanoff in [24].

Local impact needs to be studied as well due to the typically thin top face plates. The behaviour of steel sandwich panels under local impact loading was investigated by means of laboratory testing, FE simulations and analytical modelling [25]. The FE simulations enabled the following of the impact process and attainment of the information about the behaviour of a panel throughout the impact. Based on this and the observation during the laboratory experiments, an analytical model has been developed analysing the deformation energy. The deformation energy, in case of the panel with filling, can be partitioned into three main components: bending and membrane energy of the top plate and energy absorbed by the filling material. Deformation depth and the shape can be then evaluated by equalising the kinetic energy of the striking body with the deformation energy of the panel as shown by Tabri in [25].

4.3 Joints

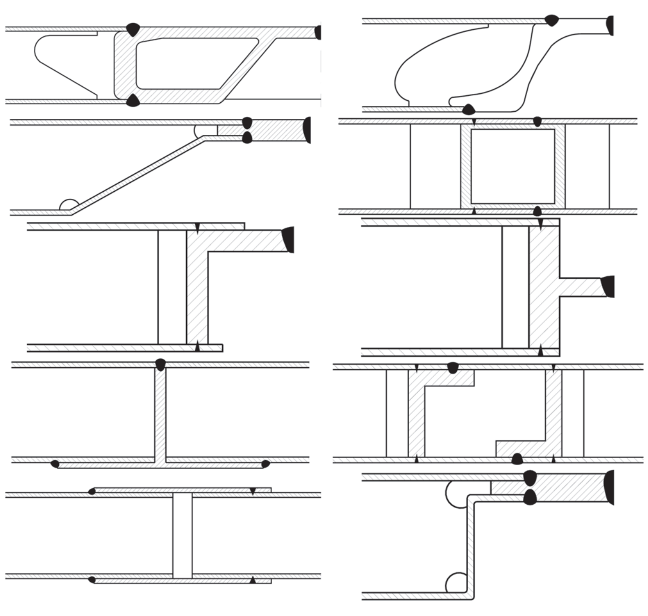
Particular problems in highly loaded sandwich structures are joints. The joining element has to enable a simple connection of panels by single side conventional butt welding. Hence, the sandwich structure can be connected to the surrounding structure in a way similar to conventionally stiffened plates. Figure 4 illustrates typical solutions for the joining elements.

The main design topics of joints are related to the fatigue properties and how to determine the fatigue strength when attributed with high longitudinal and in particular shear loads. No fatigue design catalogues for steel sandwich joints is available at present in public literature.

During the SANDWICH research project, the joints were analysed under longitudinal load along the core applied at the

Figure 4 **Typical solutions for the joining elements of steel sandwich panels [27]**

Slika 4 **Tipična rješenja spojnih elemenata za čelične sendvič panele [27]**



other end of the panel, see Figure 5. The Radaj's approach [26] was used to determine the stress concentration factors for typical joints as reported by Ehlers in [27]. A circle of 1 mm in diameter is modelled on the critical areas enabling thus more exact stress evaluation, see Figure 6.

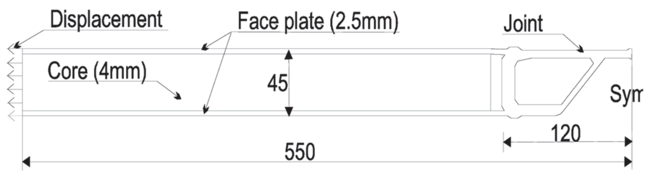


Figure 5 **The studied load case for the joints [26]**
Slika 5 **Proučavani slučaj opterećenja za spojeve [26]**

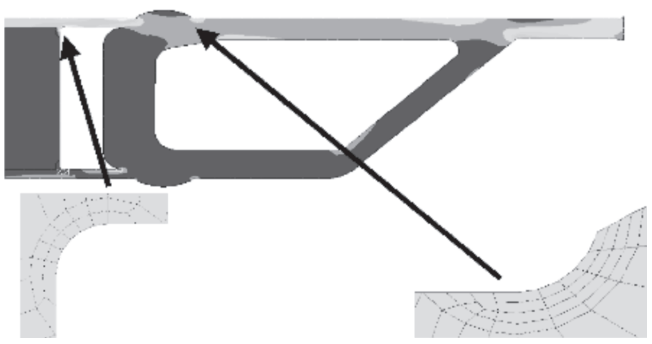
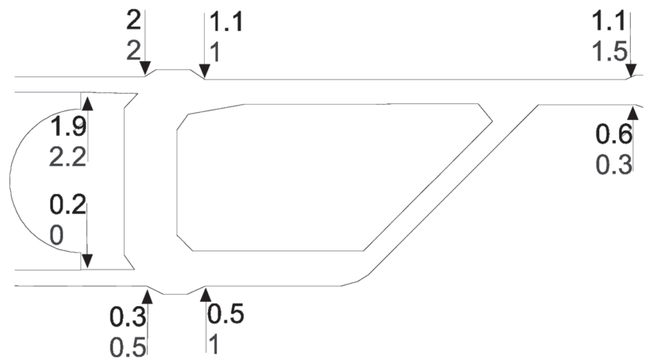


Figure 6 **The modelling principles applying the Radaj's circles on the hot spot areas [26]**
Slika 6 **Načelo modeliranja primjenom Radajevih krugova na područjima žarišnog naprezanja [26]**

Figure 7 illustrates example of the calculated stress concentration factors. As seen, it is possible with certain joint designs to achieve values for the stress concentration factor varying between 2 to 3, which are fairly acceptable values. The upper values are for symmetric loading at the ends and the lower values for the asymmetric load, or the load acting only at the bottom plate. Although this indicates that joints with a high fatigue performance are possible, being mainly symmetric, often present problems in fitting and welding under assembly conditions. Since the 2D FE models assume homogenous and equal material properties for the weld and base material, any welding defect or production effects are not taken into account.

Figure 7 **Examples of joints with calculated stress concentration factors [26]**
Slika 7 **Primjeri spojeva sa izračunatim faktorima koncentracije naprezanja [26]**

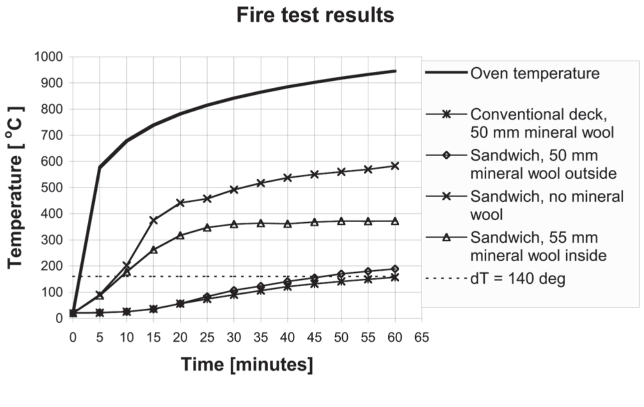


4.4 Fire safety

For most applications of steel sandwich panels, the fire safety is an important consideration. Since these panels consist only from steel, their behaviour under fire is typically similar to conventional steel structures. An example of the results of the fire resistance tests are given in Figure 8 [28]. In these tests the dimensions of the pieces were 1.25 m × 1.25 m. The height of the *Lascor* steel sandwich was 50 mm with top and bottom plate thicknesses of 1.0 mm and the corrugated core 0.7 mm. Conventional stiffened plating with plate thickness of 5 mm with 50 mm mineral wool (PV-F-110 L) was used as a reference case. Three tests were conducted with the sandwich structure: 1) no mineral wool, 2) 50 mm mineral wool outside the sandwich panel and 3) 55 mm mineral wool inside the sandwich panel. The temperature of the furnace was rapidly increased so that in the end of test the temperature was above standard 900 °C. The mean temperature of the colder surface is one aspect that determines the fire class of the structure. The time required for the increase of the mean temperature to 140 °C along with other requirements specifies the fire class so that fire class A60 means that it takes longer than 60 minutes to achieve this reference temperature increase.

As can be seen from Figure 8, the conventional stiffened plating with 50 mm mineral wool fulfils the A60 requirement and *Lascor* sandwich panel with 50 mm mineral wool against fire is close to the A60 requirement. The insulation inside the *Lascor* is not as effective as the insulation outside the panel. The fire characteristics of the sandwich panel can be remarkably increased by using holes on the corrugated core plating (Figure 9), as this will decrease the thermal conductivity of the webs. For the sandwich panel the installation of mineral wool outside is also a lot easier than for the conventional deck structures with numerous stiffeners to be surrounded by mineral wool whereas for sandwiches, the coatings can be attached on a flat surface.

Figure 8 **Comparison of sandwich panel fire characteristics with conventional deck structure [28]**
Slika 8 **Usporedba požarnih karakteristika sendvič panela i konvencionalne palubne konstrukcije [28]**



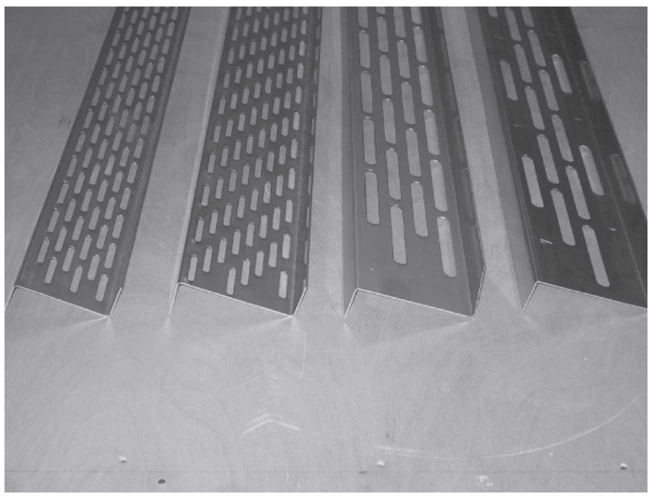
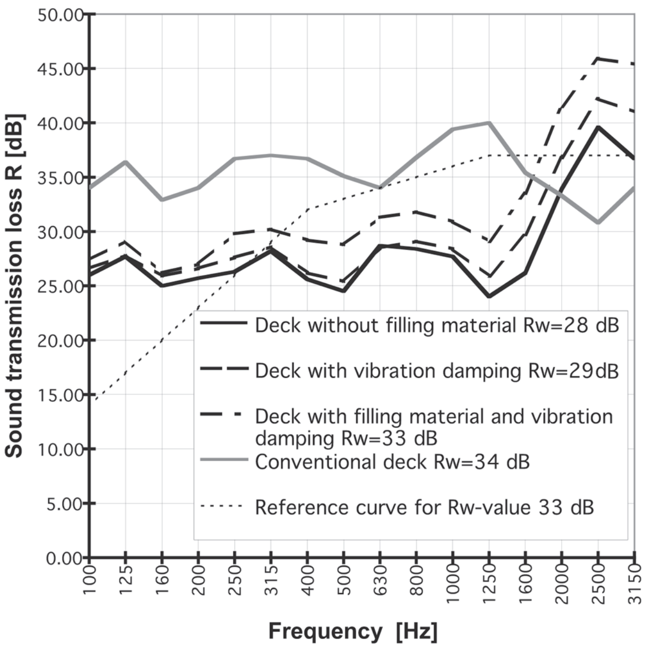


Figure 9 **The behaviour of steel sandwich under fire can be improved by using holes on the core plates [28]**
Slika 9 **Ponašanje čeličnog sendvič panela izloženog vatri može se poboljšati bušenjem rupa na pločama jezgre [28]**

4.5 Noise

Noise behaviour of all steel sandwich panels is a special issue which has not been widely studied so far. Reference [28] shows an example of noise behaviour based on the laboratory measurements, see Figure 10. It has been found that the sandwich panel has better sound absorption characteristics than the conventional panel at sound frequencies higher than 1600 Hz, but at lower frequencies the conventional panel is somewhat better. A higher mass of the conventional panel is the main reason for a higher sound transmission loss at lower frequencies. The improvement of the insulation properties for the sandwich panel was studied by putting a thin rubber mass on the panel surface and mineral wool inside the panel. That somewhat increased the sound transmission losses, being *R*w=33 dB, through the panel, but the increase is not sufficient to achieve the sound loss level of the conventional panel in the frequency range from 300 to 1600 Hz. If high noise transmission losses are required then additional floating covers are needed on the top or on the bottom of sandwich panels.

Figure 10 **The measured sound transmission loss as a function of the sound frequency for the tested steel sandwich panels [28]**
Slika 10 **Izmjereni gubitak pri prijenosu zvuka kao funkcija frekvencije zvuka za testirane čelične sendvič panele [28]**



5 Case study - optimisation of a steel sandwich hoistable cardeck

5.1 Scope

In order to demonstrate benefits of steel sandwich panels we present one application in ship structures. A traditionally built hoistable cardeck, a representative increment/segment of which is seen in Figure 11, was redesigned with respect to minimum weight and cost, applying the I-Core panel for decking. A similar study was performed for the Vf-Core panel [29], however, this study did not consider optimisation of the supporting grillage structure.

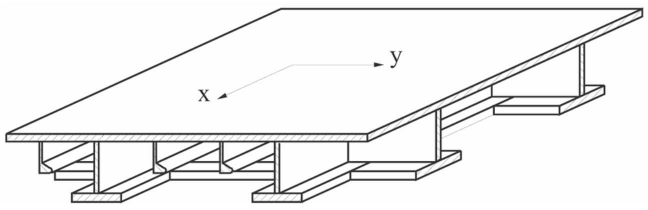
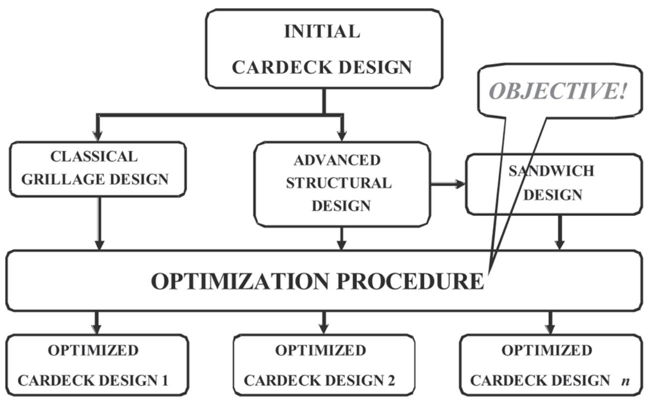


Figure 11 **Increment/segment of a traditionally built cardeck of the Variant A**
Slika 11 **Segment tradicionalno građene palube za vozila, inačica A**

In Figure 12 we can see a diagram for the redesign process of a cardeck that results in several new optimised designs. After suggesting improvements, such as the application of sandwich panels, designer uses optimisation procedure to obtain the final optimised designs that can be compared and selects one design.

Figure 12 **Diagram for redesigning a cardeck [30]**
Slika 12 **Dijagram redizajna palube za vozila [30]**



A key part of this diagram is the optimisation procedure presented in [30] that with the help of some optimisation algorithm automatically defines the optimum structures according to the designer's input.

5.2 Description of the study

The cardeck of interest, with properties given in Figure 13 and Table 1, is simply supported by pillars in four corners. Figure 14 shows how the cardeck is used on a ship as one part of a global cardeck. The cardeck is considered to be loaded by commercial vehicles that exert a local load of p_{Loc} = 250 kPa on tire print. There are 9 vehicles on the deck, so their total weight is modelled with water pressure as global load of p_{Glob} = 3 kPa. These loads account for the motions of ship in waves, with characteristics given in Table 1.

Two alternative concepts are proposed for redesign: sandwich-grillage cardeck (Variant B), a sandwich panelled cardeck with grillage supporting structure seen in Figure 15; sandwich cardeck (Variant C), a sandwich panelled cardeck that only uses C girders on perimeter, seen in Figure 16.

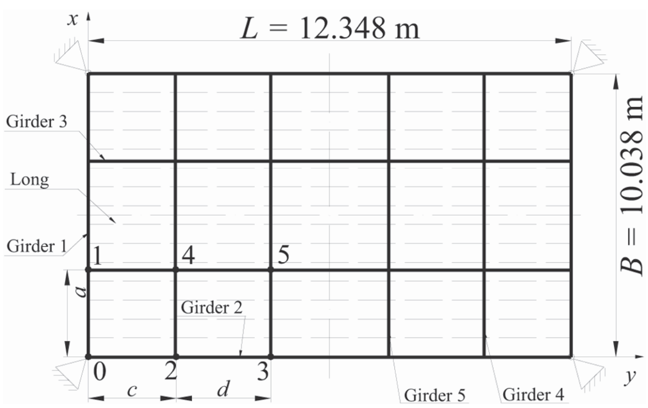


Figure 13 **Top view of the cardeck with main dimensions**
Slika 13 **Pogled odozgo na palubu za vozila i osnovne izmjere**

Table 1 **Main particulars of the ship**
Tablica 1 **Osnovne izmjere broda**

Length between perpendiculars, L_{pp} [m]	165.00
Breadth, B [m]	31.10
Draught, T [m]	8.75
Block coefficient, C_B	0.54
Speed in service, V [kn]	19.0

The sandwich panel is considered to be filled with polyurethane to increase several properties, among them, the corrosion protection. Yet, the structural benefits, noted in [24] and in [25], were not taken into account. Nevertheless the costs were calculated and added to the total production expenses.

On top of two alternative concepts, the initial design (Variant A), was also optimised so that the comparison of the design concepts can be established at the same level.

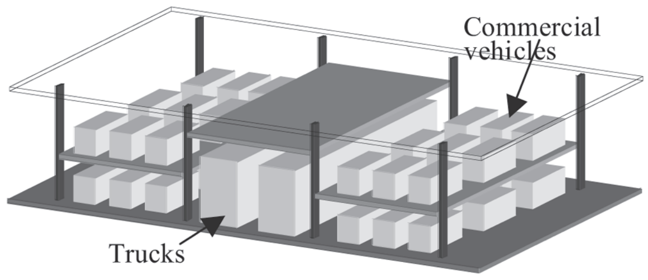


Figure 14 **Usage of cardeck in working (loaded by commercial vehicles) and stowed position, to allow loading of high vehicles, like lorries**
Slika 14 **Paluba za vozila u radnom (natovarena komercijalnim vozilima) i ukrcanom položaju, omogućen ukrcaj visokih vozila kao što su kamioni**

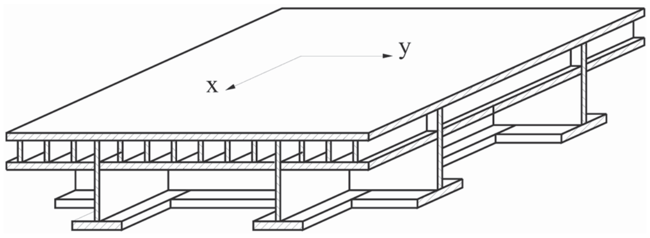


Figure 15 **Increment /segment of the Variant B**
Slika 15 **Segment inačice B**

5.3 Design variables

The design variables included the scantlings of:

- Plating thickness (variant A only)
- Sandwich panel (variants B and C only)
- Scantlings of girders
- Geometry of grillage (variants A and B only)

Design variables for Variants A, B and C are seen in Figure 17, 18 and 19, respectively.

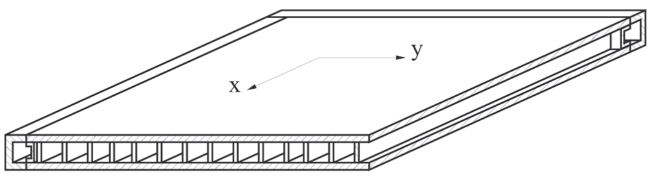


Figure 16 **Increment/segment of the Variant C**
Slika 16 **Segment inačice C**

Following the complexity of the proposed redesigns the number of design variables varied comparatively, so the design variant A had 20 variables, B had 24, and C had 11. All the variables were treated as continuous variables. Bulb flats in Variant A were not optimised.

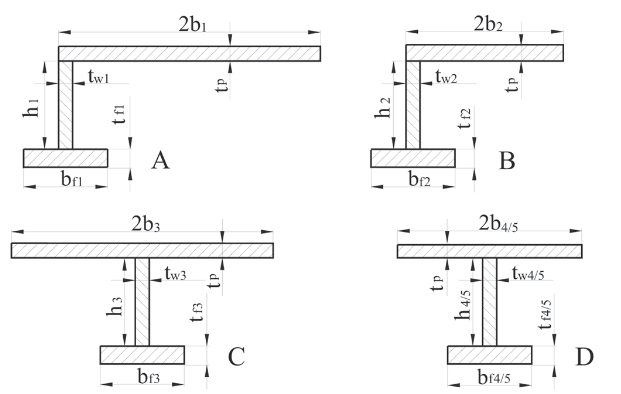


Figure 17 **Design variables of Variant A, for a) girder 1, b) girder 2, c) girder 3 and d) girders 4 and 5**

Slika 17 **Projektne variable inačice A , za a) nosač 1, b) nosač 2, c) nosač 3 i d) nosače 4 i 5**

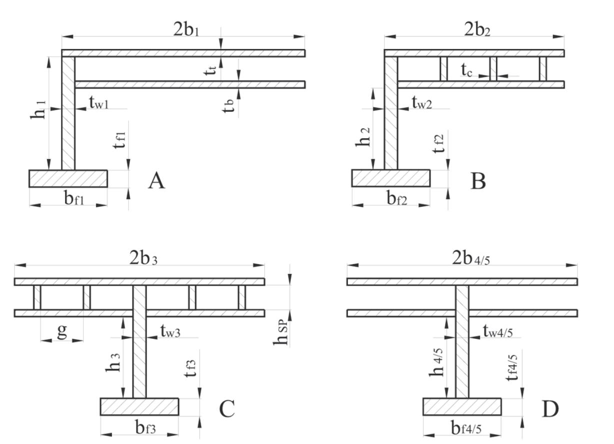
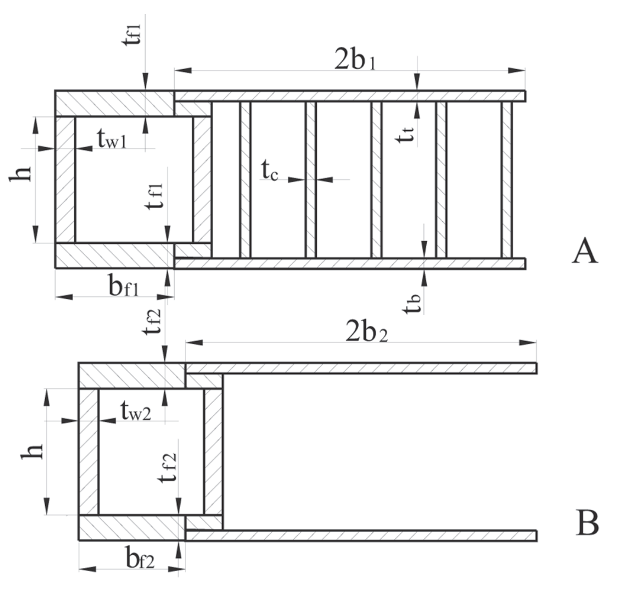


Figure 18 **Design variables of Variant B, for a) girder 1, b) girder 2, c) girder 3 and d) girders 4 and 5**

Slika 18 **Projektne variable inačice B , za a) nosač 1, b) nosač 2, c) nosač 3 i d) nosače 4 i 5**

Figure 19 **Design variables of Variant C, for a) girder 1 and b) girder 2**

Slika 19 **Projektne variable inačice C , za a) nosač 1, b) nosač 2**



5.4 Design criteria

The hoistable cardeck was optimised for two criteria, the weight and the cost of production, separately, hence optimum structures were defined for each objective functions. Evaluation of these two objective functions is straightforward, and they are often expressed per unit area of the panel. Production cost is computed from three different parts, cost of: 1) material, 2) labour and 3) overheads as summarised by Rigo in [31]. The cost of material is found on the basis of weight, by multiplying the weight with the cost coefficient that is dependent on the thickness of plates and size of rolled profiles (built-up profiles are made of plates). In addition, if a panel is filled with a core filling material, such as polyurethane, then the price of this material is included in calculations. Labour costs are generally evaluated on the basis of workload or needed man-hours. They could be separated into costs needed to produce steel sandwich panel and to produce grillage. Sandwich panel is produced by laser welding in an automated production facility and the costs are separated into welding costs and preparation costs as described in [32] and [28]. Welding costs are dependent on weld length, while preparation costs are calculated as a function of panelled area. Labour costs needed to produce the grillage structure are based on the welding length. Overhead costs include expenses of electricity, welding electrodes, amortisation of equipment, etc. These are calculated again on the basis of length of welds.

The cost of production was evaluated for the virtual workshop, which was placed in the country with high standard of living and had a relatively small production efficiency. This assumption would resemble a workshop in a company that has just started the business of producing hoistable cardecks.

5.5 Constraints

According to the mathematical modelling of cardeck as a grillage, for variants A and B, and combined beam – orthotropic plate for Variant C, applied constraints were the following:

For Variant A:

- Buckling and indentation of plating
- Buckling and yielding of *T*- girders' webs
- Yielding of *T*-girders' flanges

For Variant B:

- Buckling and indentation of SP's top faceplate
- Buckling, yielding and plastic collapse of SP's core
- Buckling and yielding of a SP's bottom faceplate
- Buckling and yielding of a *T*- girders' webs
- Yielding of a *T*- girders' flanges

For Variant C:

- Buckling and indentation of SP's top faceplate
- Buckling, yielding and plastic collapse of SP's core
- Buckling and yielding of a SP's bottom faceplate
- Buckling and yielding on a *C*- girders' webs
- Yielding of a *C*- girders' flanges

For all three variants maximum allowed deflection constraint was applied in the amount of $\mathbf{w}_{awd}$ = 50 mm. The constraints formulae are described in detail in [32].

5.6 Parameters of genetic algorithm

Formulations for calculating objective functions, response and constraints were coded by C++ as an input file for the genetic algorithm *Gallops* [33]. Parameters from Table 2 were used to find the optimum structure in 10000 generations. It was noticed that much better results were reached with unusually high probabilities of crossover and mutation.

5.7 Results

Overall results are presented in Table 3. Minimum weight design of Variant C was found to be the one offering considerable weight savings of about 28 % and maximum of cost savings of about 20 %.

Design Variant A did not results in any noticeable improvements. Minimum weight design offered only savings of about 11 %, but considering that the values of design variables have to be rounded off to at lease 0.5 mm the savings could be lost. The conclusions can be drawn from this that the initial design was quite close to the optimum and that further major improvements with the traditional structures are limited.

Table 2 **Parameters of optimisation**
Tablca 2 **Parametri optimizacije**

Parameter	A	B	C
α	100		
Length of the chromosome	140	168	77
P – weight [kg]	15000	20000	15000
P – cost [€]	45000	40000	30000
No. of generations, n_G	10000		
Population size, n_p	30		
Probability of crossing over, p_c	0.91		
Probability of mutation, p_m	0.33		

Table 3 **Results of the optimisation (values of best design are underlined)**
Tablica 3 **Rezultati optimizacije (vrijednosti najboljeg dizajna su podvučene)**

Variant	Initial	A		B		C	
Design variable	design	Wt.	Cost	Wt.	Cost	Wt.	Cost
Spacing between girders 2 I 3, a [mm]	3820	4819	4685	3257	4819	-	
Spacing between girders 1 I 4, c [mm]	2424	3902	3376	1811	3379		
Spacing between girders 4 I 5, d [mm]	2500	557	1184	452	505		
Plating thickness, t_p [mm]	6.0	6.5	6.5	-			
Top faceplate thickness, t_t [mm]				2.0	4.5	4.5	6.5
Core plate thickness , t_c [mm]				3.0	4.5	2.5	2.5
Bottom faceplate thickness , t_b [mm]				1.5	2.5	2.0	5.5
Core spacing, g [mm]				68.0	282.0	305.0	436.0
Height of the sandwich panel, h_{SP} [mm]				26.0	25.0	300.0	203.0
Webplate thickness of girder 1, t_{w1} [mm]	6.0	6.5	6.0	6.0	6.0	6	6
Flange thickness of girder 1, t_{f1} [mm]	25.0	26.0	12.6	6.0	6.0	6	6
Flange breadth of girder 1, b_{f1}	260.0	58.0	115.0	50.0	50.0	50	50
Height of girder 1, h_1 [mm]	300.0	294.0	209.0	300	300		
Web plate thickness of girder 2, t_{w2} [mm]	6.0	6.0	6.0	6.0	6.0	6	6
Flange thickness of girder 2, t_{f2} [mm]	25.0	29.0	29.0	6.0	6.0	6	6
Flange breadth of girder 2, b_{f2} [mm]	330.0	202.0	270.0	53.0	50.0	53	50
Height of girder 2, h_2 [mm]	300.0	300.0	298.0	300.0	300.0		
Webplate thickness of girder 3, t_{w3} [mm]	6.0	6.0	6.0	6.0	6.0		
Flange thickness of girder 3, t_{f3} [mm]	25.0	10.0	10.0	29.0	10.0		
Flange breadth of girder 3, b_{f3} [mm]	230.0	50.0	59.0	138.0	53.0		
Height of girder 3, h_3 [mm]	300.0	100.0	104.0	300.0	296.0		
Webplate thick. of girders 4 and 5, t_{w45} [mm]	6.0	6.0	6.0	6.0	6.0		
Flange thickness of girders 4 and 5, t_{f45} [mm]	10.0	26.0	22.0	29.0	19.0		
Flange breadth of girders 4 and 5, b_{f45} [mm]	200.0	114.0	192.0	130.0	166.0		
Height of girders 4 and 5, h_{45} [mm]	300.0	300.0	300.0	300.0	300.0		
Weight [kg]	**13160**	**11678**	**11950**	**9320**	**11190**	**9462**	**13100**
Specific weight [kg/m²]	**107**	**94**	**96**	**75**	**90**	**76**	**105**
Cost of production [€]	**36300**	**36280**	**36040**	**3521**	**30640**	**30190**	**28920**
Specific cost of production [€/m²]	**263**	**293**	**291**	**284**	**247**	**243**	**233**

Outcome of the optimisation of design variant B offers absolute minimum weight design, but variant C wins due to lower costs of production. Nevertheless, variant B is a good potential design solution that leads to conclusion that sandwich panelling, when supported by grillage is a much better solution than traditional panelling.

6 Conclusions

There has been a lot of research activities in Europe related to the development of laser welded steel sandwich panels. The work carried out includes the development of design formulations for the ultimate and impact strength, analysis of fatigue strength for the joints, and development of solutions to improve the behaviour under fire and noise. New factories have been established to produce these types of panels, which enables larger scale implementations of the panels for various types of ships in the near future.

Optimal design of steel sandwich panel applications in ships is a complex task, comprising many subtasks, such as load modelling, response calculations and optimisation. Following this principle, a redesign of hoistable cardeck was performed, including the minimisation of weight and cost of production. Two advanced sandwich alternatives were suggested instead of the traditional panelled structure and were then optimised.

Paper gives evidence that the hoistable cardeck with sandwich panelling can now be designed in the preliminary faze without using the finite element methods. This seriously shortens the design time, which is of great importance to a designer. One optimization run, on a typical PC, took only couple of minutes, thus enabling the variability and offering more freedom to designer to explore new concepts.

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