DESIGN AND MANUFACTURE OF COMPOSITE SANDWICH PANELS FOR THE UYLLANDER BRIDGE IN AMSTERDAM

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ABSTRACT

In 2012 the new traffic bridge has been installed over the Amsterdam-Rijn-canal. This bridge, the so-called ‘Uyllanderbrug’, is constructed as a steel structure with a reinforced concrete road deck. For the casting of the concrete deck, composite sandwich panels have been developed that serve as a concreting formwork. The panels with lengths up to 15 meter have to support the concrete during casting over a span of 3,8 m. A limited deflection and a low weight were required. Moreover, the support thickness at the edges was limited, which was the major design challenge. Benefits of using the composite panels were easy installation of the concreting formwork from the top (no obstruction of the canal) and a smooth surface on the bottom side of the bridge. The design that has been developed is based on the use of optimized shear-web positioning in the composite sandwich structure. It is shown how the design started with elementary calculations that have been verified by FEM-analysis of the composite panel. In a further stage of the development prototype test panels have been manufactured and subjected to mechanical testing.

INTRODUCTION

For casting concrete the formwork serves as a casting mould. Generally this formwork is made of film-faced plywood. The formwork is then composed of the plywood panels that are strengthened by a backing structure. After casting and solidification of the concrete the formwork is dismantled. Building and dismantling of such a formwork made of plywood is labor-intensive and sometimes gives problems. In case of the Uyllanderbrug the problem was that a plywood formwork should have to be installed above the canal. This would obstruct the passage of boats on the canal.

The engineering consultants of Ingenieursbureau Amsterdam (IBA) proposed to use composite panels that can be placed in the steel structure of the bridge already on shore. After this, the bridge structure can be placed over the canal. Then, the concrete can be cast on the panels without building a formwork of plywood. Moreover, after casting and solidification of the concrete, the panels can stay in place and do not need to be removed. Because the bottom side of the panels has a smooth surface this will give a good appearance to the bridge when looked at from the canal. In this manner the shipping traffic in the canal will not be obstructed and the installation of the formwork is less labor-intensive than it would be the case when using plywood formwork. Advantages to use composite for the panels are: a low weight, a smooth surface and outside durable. In Figure 1 a photograph is given of the bridge with the composite panels in it and prior to the casting of the concrete.

In the composite panels clearly in the middle the oblong passing holes can be seen in the photograph. These passing holes were necessary for suspending tubes that are located below the bridge and needed to be connected to the steel reinforcement in the concrete deck.

Figure 1 Bridge with composite sandwich panels prior to casting concrete.

In total 72 panels had to be made with a width of 3,8 m and lengths of 11 m and 15 m, respectively. The principle of the use of the panels as formwork for casting the concrete is illustrated in Figure 2 (measures in mm).

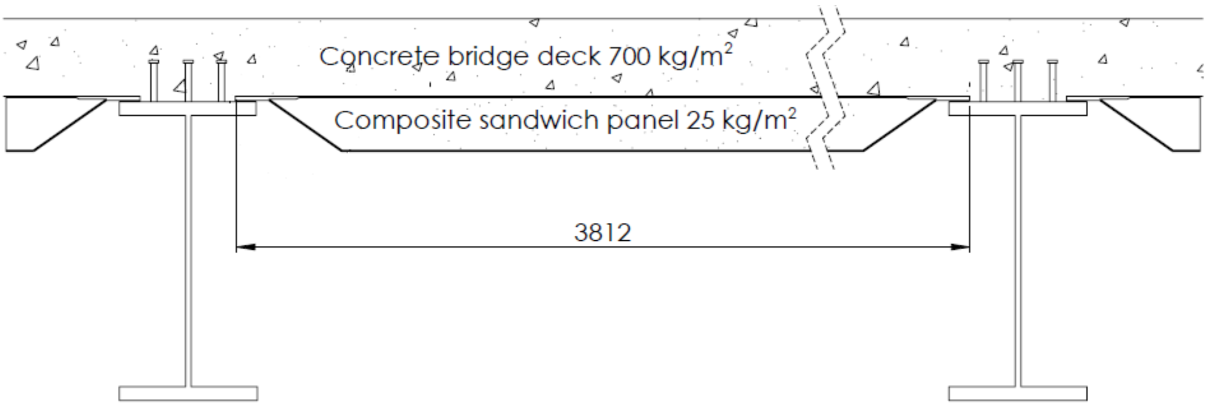

Figure 2 Principle of composite sandwichpanel as formwork for casting concrete.

PANEL REQUIREMENTS AND DESIGN PRINCIPLE

Two requirements played a dominant role in the design of the panels. In the first place the deflection in the middle of the panel should not be more than 25 mm when the concrete is cast (weight of concrete and accompanying steel reinforcement: 700 kg/m^2). Secondly the upper part of the panel should not become higher than 20 mm above the steel flanges of the supporting steel sub-structure. The former requirement implies that the use of a sandwich structure is necessary to obtain sufficient stiffness. The latter requirement involves the use of a supporting edge.

Because the location of the support should be well-defined and stress-concentrations due to surface roughness should be avoided, a supporting edge with a thickness of 15 mm is selected that is placed on a hard-rubber strip with 5 mm thickness. The details of the supporting edge are given in Figure 3 (measures in mm).

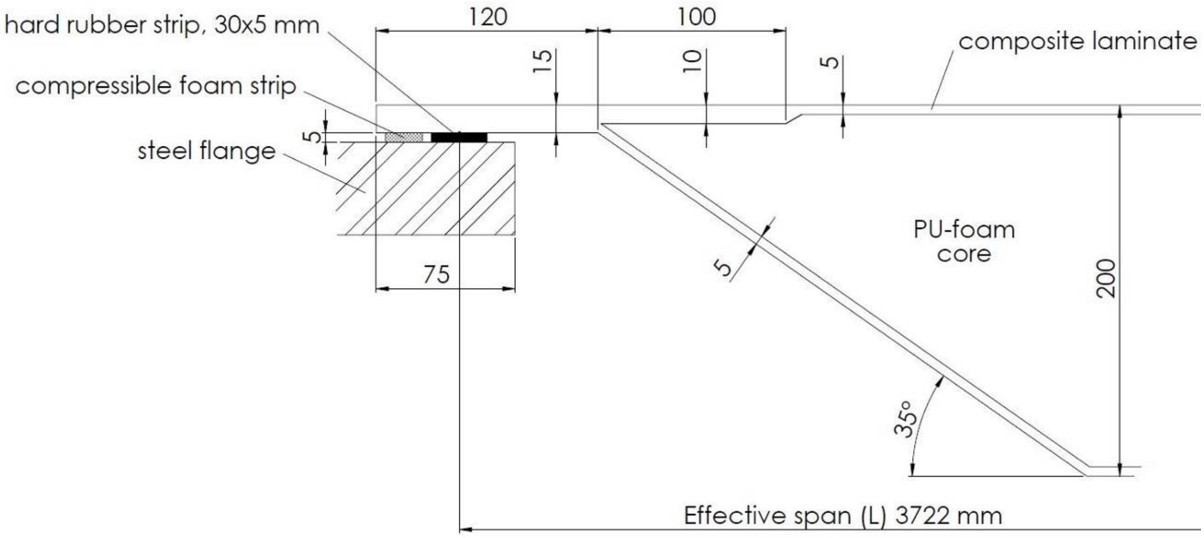

Figure 3 Details of supporting edge of the composite panel.

From the figure it is clear that the centre of the supporting hard rubber strip lies 45 mm from the panel edge. Because of bending the upper part of the panel will be loaded in compression. Because these compression stresses attain a high level where the panel does not have its full thickness of 200 mm, in the upper layer a thickness is maintained of 10 mm over a length of 100 mm. A local high concentration of shear webs in this area (not indicated in the figure) must prevent separation of the upper and the lower laminate layers.

COMPOSITE DESIGN CODES

Before proceeding with the analysis of the panel design the relevant composite design codes are discussed. At present in The Netherlands the following codes are used for composites:

Eurocode EN 1991 (1)	Loads on structures and load factors.
CUR Recommendation 96 (2)	Composite properties and material factors.

The CUR Recommendation 96 has been recently revised and translated into English. It is written in a Eurocode form and will be proposed in the task committee TC250, working group WG 4 for the realization of a Eurocode for composite materials.

For the current analysis the following factors from the design codes are relevant:

Load factor (from EN 1991): $\gamma_Q = 1.5$ (variable loading)

Material factor (from CUR 96): $\gamma_M = \gamma_{M,1} \cdot \gamma_{M,2} = 1.35 \cdot 1.2 = 1.62$

In which $\gamma_{M,1} = 1.35$ (to account for material variations)

$\gamma_{M,2} = 1.2$ (for post-cured injection moulded products)

Conversion factor (from CUR 96): $\gamma_c = \gamma_{ct} \cdot \gamma_{cv} \cdot \gamma_{cf} \cdot \gamma_{ck} = 1.0{\cdot}1.1{\cdot}1.0{\cdot}1.067 = 1.17$

In which $\gamma_{ct} = 1.0$ (maximum service temperature $T_d < T_g$ - 40°C)
$\gamma_{cv} = 1.1$ (alternating wet and dry periods)
$\gamma_{cf} = 1.067$ (creep effect UD-plies, 28 days concrete curing)
$\gamma_{ck} = 1.0$ (no fatigue; less load cycles than 5000)

For evaluating strength the following inequality is checked:

$$\sigma_{an} \cdot 1.5 \leq \sigma_d = \sigma_k / (\gamma_M \cdot \gamma_c) = \sigma_k / 1.9$$

In which σ_{an} stress that follows from analysis
σ_d the design strength
σ_k characteristic strength that follows from tests

For evaluating stiffness, no load factor nor material factor are used because the actual deflection is needed to calculate and this is not connected to safety, opposing to strength.

DETERMINATION OF MATERIAL PROPERTIES

For the design a reference laminate build up is selected as given in Table 1, describing the layers from the mould-side to the foil-side:

Table 1 Build up of reference laminate

Layer	**Areal weight (g/m^2)**	**Remarks**
Gelcoat	400	Thickness of 350 μm, applied prior to injection
Synthetic polyester fleece	60	Non-woven
Continuous filament glass mat	150	Random reinforcement
Continuous filament glass mat	450	Random reinforcement
Unidirectional glass reinforcement	890	840 g/m^2 of reinforcement in 0°-direction
Continuous filament glass mat	150	Random reinforcement
Unidirectional glass reinforcement	890	840 g/m^2 of reinforcement in 0°-direction
Continuous filament glass mat	150	Random reinforcement
(Peel ply and foil: removed after vacuum injection and curing of the product.)		

With this build up test-laminates are made by vacuum-injection with the same resin and the same injection parameters as will be done for the sandwich panels. The test-laminates have been tested in tension for the determination of tensile strength and tensile modulus in 0° direction (10 test specimens tested according to ISO 527-4) and in short-beam interlaminar shear (ILSS, 10 test specimens tested according to ISO 14130). Moreover the glass content by weight has been determined according to ASTM 2584-94. The results are given in Table 2.

Table 2 Results of tests on reference laminate

Parameter	**Unit**	**Mean value**	**Standard deviation**
Tensile strength (σ_{Lt})	MPa	296.0	14.1
Tensile modulus (E_{Lt})	GPa	15.5 (front) 17.3 (back)	1.4 (front) 0.7 (back)
Shear strength (τ_{LT})	MPa	25.7	1.6
Glass content by weight (φ)	%	41.3	0.9

Because the laminate build up is not symmetrical, strains have been measured on both sides of the test specimen, giving different results for the E-modulus determination (indicated with ‘front’ and ‘back’ in the table). For calculations the mean of these two values is used. The measured stiffness properties are used as input for the numerical simulations that are described in the following. (It goes without saying that the 0°-direction of the laminate is directed in the width-direction of the panel, i.e. the span-direction of the panel.)

NUMERICAL SIMULATIONS

Weight of the panel and the reinforced concrete is 725 kg/m^2, which can be regarded as a distributed load on the panel of 7.11 kN/m^2. The deflection of the panel will have the maximum value in the middle, U_{max} , and can be regarded to be composed of a part that is caused by pure bending of the sandwich, U_b , and a part that is caused by additional effects, U_{add}.

$$U_{max} = U_b + U_{add}$$

Additional effects are shear deformations in the foam core, the shear webs and deformations of the supporting edge. These additional effects can not be calculated by analytical methods and have been determined by numerical simulation. For this, a reference panel is modeled with a width of 1 m and a total length of 2 m. Supporting edge and sandwich build up were identical to the panels to be made. The reason for modeling this reference panel is that prior to production 5 of these reference panels were produced for testing strength and stiffness. A finite element (FEM) analysis has been performed on the reference panel. The deflection has been calculated, see Figure 4 and stresses were evaluated using the factors for load and material as described previously in this article. Special attention was paid to interlaminar shear stresses and in-plane shear stresses in the shear webs. Moreover the elastic stability has been verified of the upper skin laminate and of the shear webs. In all cases an acceptable level of stresses with regard to strength and stability was found.

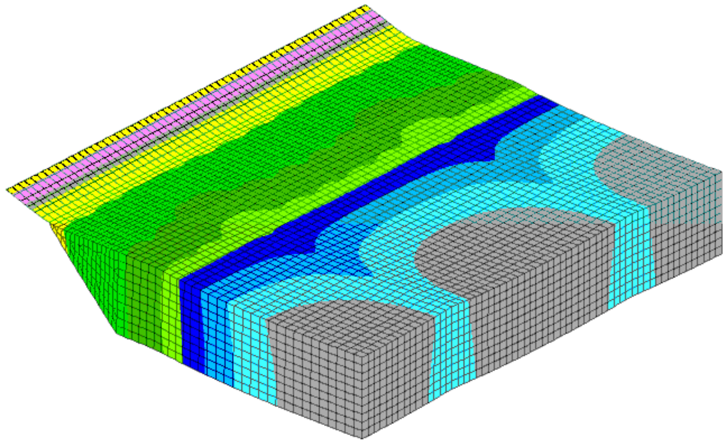

Figure 4 Contour plot of vertical displacement of the FEM-model.

From the FEM-analysis the deflection due to the additional effects was calculated for the full-size panel with the actual weight loading and was found to be U_{add} = 4.8 mm. Pure bending of the full-size panel is calculated by considering the panel as a sandwich with a thickness H = 200 mm and a skin-thickness of t = 3.4 mm. For a representative width, W, the moment of inertia, I, can be approximated with the formula:

$$I \approx ½ W t H^2$$

With the classical formula for a simply supported beam with a distributed load the deflection caused by pure bending can be calculated:

$$U_b = 5 q L^4 / 384 E I = 15.6 \text{ mm}$$

Thus the total deflection of the full-size panel is calculated to be:

$$U_{max} = U_b + U_{add} = 15.6 + 4.8 = 20.6 \text{ mm}$$

This is below the maximum value of 25 mm. In production the panels were made with an upward arch of 25 mm so that after casting the concrete the panels will become practically flat at the bottom side. This is done in view of aesthetics.

EXPERIMENTAL VERIFICATION

As indicated during the project it was required to make 5 test panels to verify the strength and stiffness that was found by analysis. In Figure 5 the test set-up for a three-point bending test on the panels is illustrated (measures in mm, unless indicated otherwise).

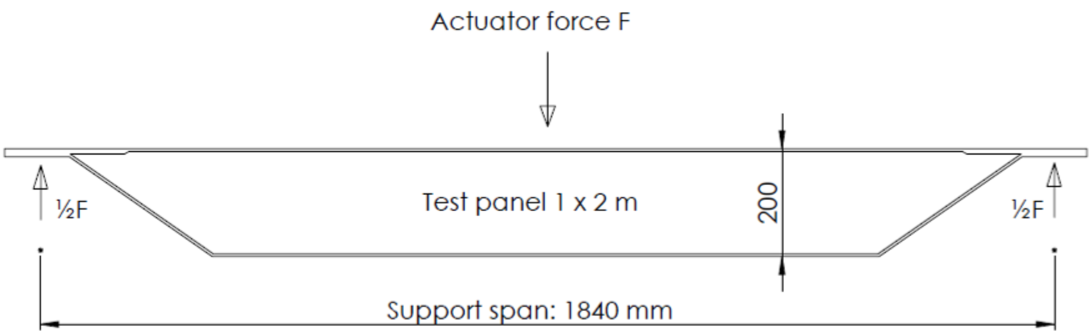

Figure 5 Set-up for three-point bending test on test-panels.

For each panel the force in the middle is applied as a line force. From an unloaded situation the force first is increased to 30 kN in one minute and held at this load level for one minute. The 30 kN load on the test panel in three-point bending gives the same support reactions and the same maximum bending moment as is the case for the distributed loading of 7.11 kN/m^2 on the full-scale panels. After the loading until 30 kN, the load is decreased to 0 kN, after which the panel is loaded until failure in approximately two minutes. The results of the tests are summarized in Table 3.

Table 3 Results of tests on testpanels of 1 x 2 m

Panel	**Deflection at 30 kN (mm)**	**Load at break (kN) / failure mode**
1	12.3	50.4 / delamination upper skin laminate
2	10.5	46.2 / delamination upper skin laminate
3	9.8	56.6 / delamination upper skin laminate
4	10.0	51.4 / delamination upper skin laminate
5	11.7	48.6 / delamination upper skin laminate
Estimation from analysis	7.1	92.5 / delamination upper skin laminate

The measured deflections are higher than estimated from analysis (7.1 mm). This is partly caused by the fact that the supports of the panels in the test were covered with 5 mm hard rubber strips to avoid local stresses. This gave a contribution to the measured deflection. The critical part for failure is the stability of the upper skin laminate due to compressive stresses. From analysis this follows from the classical formula for the critical compressive stress in a skin laminate of a sandwich (3):

$$\sigma_c = 0.6\,(E_{foam} \cdot G_{foam} \cdot E_{skin})^{1/3} = 37\ \mathrm{N/mm^2}$$

The actual failure load is lower than predicted because of the fact that in the test the stabilizing effect of the vertical distributed weight load is missing. Moreover it has been observed during the test that the delamination of the upper skin laminate from the foam core has been initiated from the sides of the panels, where the reinforcement was interrupted.

In the actual panel build up there is the stabilizing action of the distributed load and there is a continuous upper skin. At the edges of the produced panels extra reinforcement is added to ensure a strong connection between the upper skin laminate and the side laminates.

REINFORCEMENT AROUND PASSING HOLES

A specific point of attention was the presence of oblong passing holes in the middle of the panel. For installing pipes below the bridge it was necessary to have steel strips that are connected to the reinforcement in the concrete passing through the composite panels to hang the pipes on. In Figure 6 below shows a cross-section of the situation and the dimensions of the hole at the bottom of the panel, where the passing hole has the largest dimensions.

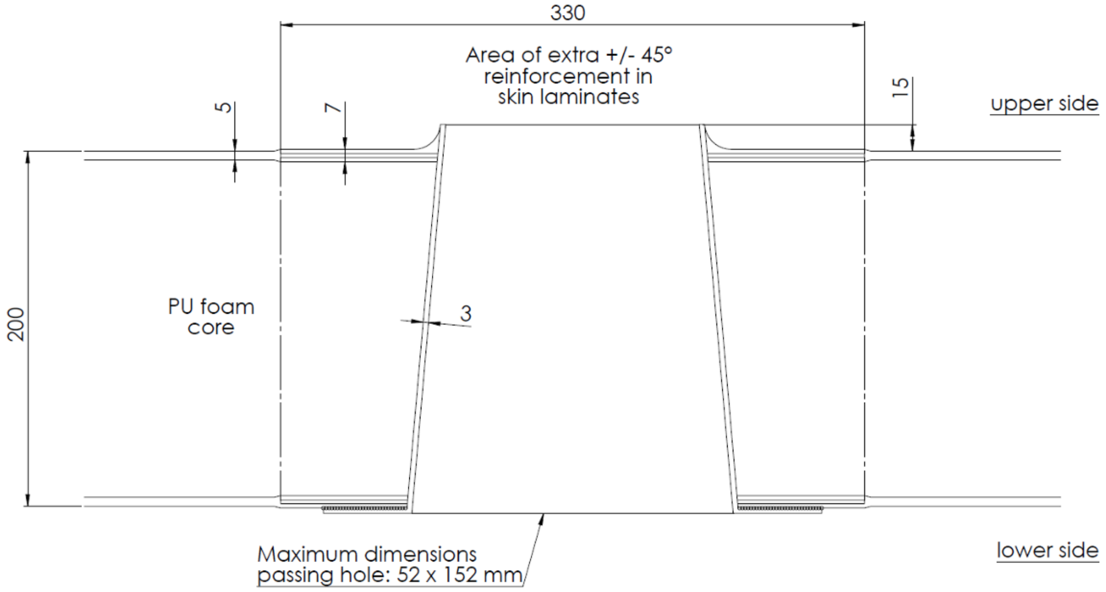

Figure 6 Cross-section and dimensions of a passing hole.

Due to the passing hole locally the UD-reinforcement is interrupted. This results in shear stresses in the skin-laminates that occur at the imaginary extensions of the sides of the hole. These shear stresses have been analysed by using the shear-lag theory that has been described by Cox (4). Without describing this analysis in detail in this article it has been found that a the solution for these local in-plane shear stresses has been to incorporate in the middle of each skin laminate a 330 mm wide bi-directional +/- 45° glass reinforcement layer of 400 g/m^2.

PRODUCTION PROCESS

For the production of the 72 composite sandwich panels it was obvious to select vacuum infusion under foil (vacuum-injection) as the production process. Clearly the hand lay-up technique would not be suitable for this because of the complicated foam core with shear webs. Moreover with hand lay-up the high glass content, low weight of the panels and the production efficiency would in this case not be possible. On the other hand production by means of RTM (resin transfer moulding) is not selected because for this series the necessary rigid upper mould would involve much extra cost and production space, because after curing of the product, the upper mould must then be taken off the product and be placed aside.

In order to optimize the resin injection strategy a flow simulation programme has been used. This resulted in an optimum distribution of resin injection channels and vacuum suction points. This is illustrated in Figure 7 where the optimized flow simulation (left) was applied in the production (right).

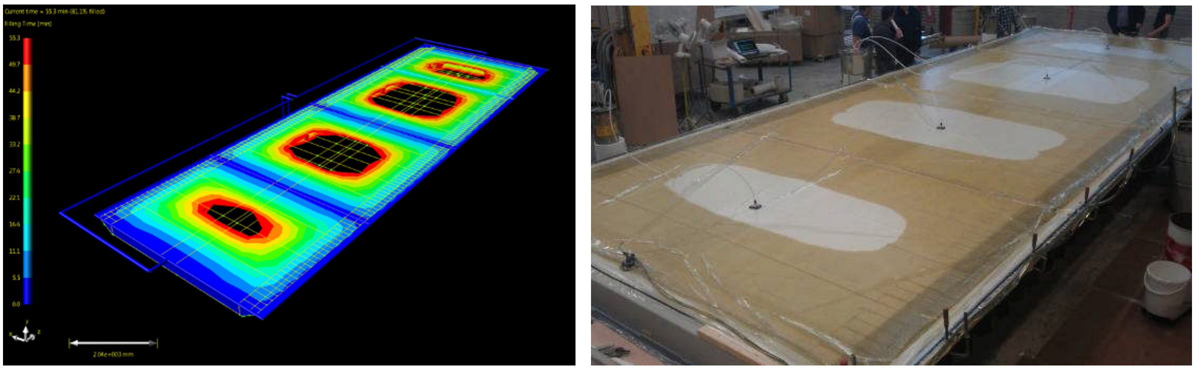

Figure 7 Flow-simulation (left) and vacuum-infusion of the panels in production (right).

After injection and curing of the product the panel is released from the mould. After this, the edges were trimmed and the passing holes were drilled and foreseen with a 3 mm composite finishing tube as depicted in Figure 6.

CONCLUSIONS

Composite sandwich panels can be designed as formwork for casting concrete. This can give major advantages over formwork that is made of plywood because the composite formwork has a low weight, can have a smooth surface and can stay in its place because of the outside durability. This saves a dismantling operation of the formwork after the concrete has solidified. The use of a formwork of composite sandwich panels has been carried out for the Uyllander bridge where the composite panels could meet the requirements of a low weight and high stiffness and strength. In a process of design and analysis and verification by tests it has been shown that the special design requirement of thin supporting edges was possible by using an optimized placing of shear-webs at this location.

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