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Situated around 31 miles to the Southeast of Istanbul, the Izmit Bay Bridge is the suspension bridge with the 2nd longest main span in the world. As the location is situated in one of the world's most active seismic zones, the bridge is designed to resist earthquakes of magnitude up to 8. MAURER successfully fulfilled the challenging task to design special expansion joints with fuse box, which in case of earthquakes shall accommodate movements of up to $\pm 3,8$ m, while remaining trafficable after the seismic event.

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Development of an innovative sandwich plate for trough-type railway bridges

Extremely slender deck slab structure in steel-concrete composite design with cellular longitudinal shear connectors

Substitute structures for old railway bridges with open railway tracks, which are constructed in accordance with valid European standards and regulations, require a specific, suitable deck slab design. Therefore, a composite plate with cellular longitudinal shear connectors and a low overall depth of 200 mm has been investigated at the Research Centre of Steel Structures (TU Wien). The research programme comprised experimental studies as well as additional numerical analyses by means of the finite element method concerning the shear force transmission-mechanism of the sandwich design. Laboratory studies included, among other issues, information about the failure mechanism in the core concrete. This article provides a description of the test program and gives a brief summary of selected research results. A short overview on continuing research activities to determine the serviceability, the load-bearing capacity as well as the fatigue strength of the sandwich plate is presented.

1 Introduction

Railway bridges with open railway tracks, where the wooden sleepers are mounted directly on the main steel structure of the bridge, are characterized by a low overall height between rail level and the underside of the bridge. An increasing number of short-span single-track structures of this type have been reaching the end of their technical service life and need to be refurbished or replaced by modern structures. In addition to the obvious requirement of compliance with the ultimate and serviceability state design for bridge structures as well as the verification of the fatigue strength, newly designed bridges must also comply with the normative requirements of noise control by using a ballast bed or a non-ballasted track. Both superstructure systems require a significantly greater depth than an open railway track. Furthermore, the clearance under the bridges and the level of the rails represent unchangeable conditions when taking account of economic aspects. Therefore, the planning task for the deck slabs of substitute bridges is to ensure a minimal overall depth based on the fixed specifications of the existing railway bridges, which manifests itself in the use of extremely slender deck slab structures. This basic premise largely corresponds with the need to optimize the consumption of materials.

1.1 Research focus

When considering a single-track trough-type railway bridge with a ballast bed corresponding to Fig. 1, numerous deck slab types are possible. Here, it is worth mentioning examples of common plate structures such as longitudinally or transversely oriented orthotropic plates as well as conventional composite structures. A comparative evaluation of these construction types including a detailed list of advantages versus disadvantages is summarized in [1]. The comparison is based on the following criteria: dead load of the load-carrying system, expenditure on corrosion protection measures, weld seam volume, and required overall height. Usual construction types of a transversely oriented orthotropic plate with an overall height of 400 mm have a dead load of approximate 15 kN per metre bridge (design according to [12]) whereas a composite deck slab with an overall height of 362 mm weights approximate 40 kN/m (composite design according to [11], Section 9), pursuant to [1]. Furthermore, all plate structures require relatively high technical expenditure on sealing and/or corrosion protection. As a consequence, substitution bridges with a 120 mm thick solid steel deck slab represent the current design type for railway bridges in the Austrian Federal Railways (ÖBB) network [4] with the requirements mentioned above. This plate thickness represents the lowest limit for the possible minimal construction depth of the plate between the main girder webs. Nevertheless, the slender solid steel deck slab results in several disadvantages, including the high self-weight of 39 kN per bridge metre, the limited availability of heavy steel plates in accordance with the small order volume for short-span bridges and welded joints that are very challenging technically. Owing to

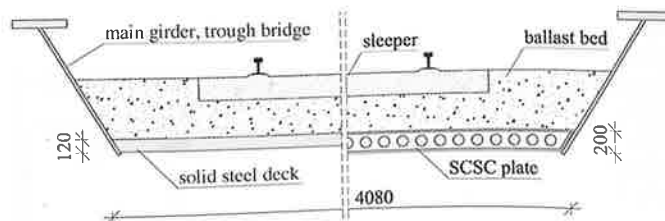


Fig. 1. Typical trough bridge section with ballast bed. Comparison of two deck slab systems; left: 120 mm thick solid steel deck slab; right: 200 mm deep SCSC plate. Dims. in mm. Institute of Structural Engineering, TU Wien [1]

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these problems, the Institute of Structural Engineering at TU Wien (Viennese University of Technology) is developing a new, alternative deck slab system in a steel-concrete composite design.

The new deck slab system undergoing development, the so-called SCSC (steel-concrete-steel composite) plate, consists primarily of two thin external steel layers, longitudinal shear connectors made from steel plates with circular cut-outs and an unreinforced concrete core. The system depth of this sandwich plate amounts to 200 mm (see Fig. 1).

1.2 Historical overview of the development of castellated longitudinal shear connectors

A new interlocking connector for securing in-situ concrete to steel girders – consisting of a steel plate 10 mm in thickness with holes of 35 mm diameter – as an alternative to stud connectors was first described in scientific literature in 1985 [5]. Further experimental tests and theoretical considerations on bonding means for composite structures were presented in the year 1987 [6]. Herein the load carrying capacity as well as the deformation behaviour of the so-called Perfobond strips under static and dynamic loading were reported, based on the results of three push-out tests.

Many research programs on Perfobond strips were carried out in the last decade [inter alia 7, 8]. The influence of the steel plate thickness, the hole diameter as well as the hole pattern, the number of strips in parallel, the use of reinforcement and the concrete strength class on the load-carrying behaviour of castellated shear connectors were investigated. Calculation models for selected Perfobond strip designs were established on the basis of the findings obtained from large-scale tests, push-out tests as well as numerical calculations.

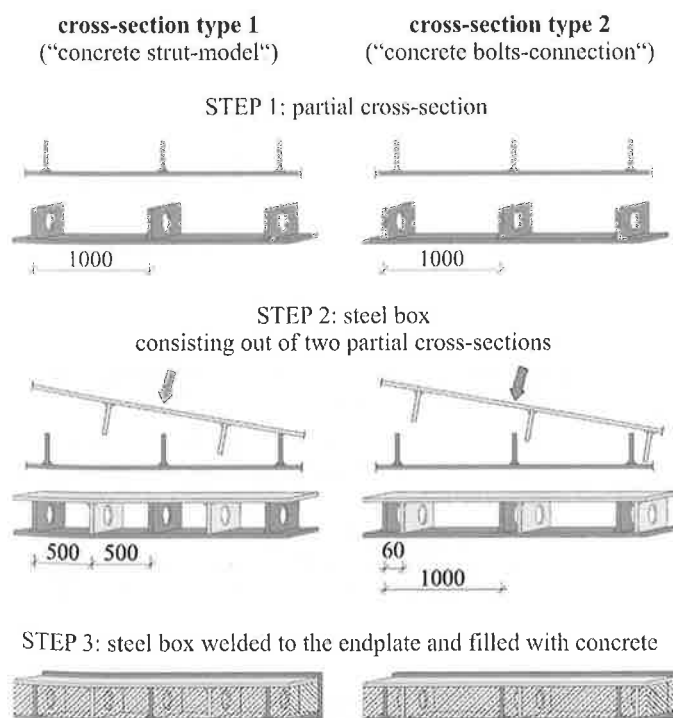


Fig. 2. Prefabrication steps for SCSC plate. Dims. in mm. Institute of Structural Engineering, TU Wien [2]

2 The SCSC plate – an innovative construction concept

The sandwich structure is planned with a low thickness of 200 mm that leads to a mass of about 3 t per metre of bridge with a span of 4080 mm between the two support lines along the webs of the main girders (Fig. 1).

Beside these benefits, the SCSC plate only features a very small surface that requires a corrosion protection coat in direct comparison to orthotropic plates. In addition, there is no need of sealing the concrete parts due to the completely sealed box-like design of the steel parts. Furthermore, it is reasonable to assume high fatigue strength of the SCSC plate owing to the cross-section design. The fatigue resistance of the SCSC plate is investigated in the course of a further research project (see Section 4).

2.1 SCSC plate cross-section

The design of the composite sandwich plate consisting of steel plates and unreinforced concrete is as follows:

- A partial steel cross-section is set up by longitudinal shear connectors (20 mm thick steel plates) with round cut-outs 100 mm in diameter which are welded to a thin steel plate 15 mm thick at a spacing of 1000 mm (see Figs. 2 and 8).
- Two of these partial cross-sections are positioned so that they fit together in a comb-like manner with a defined offset of the respective shear connectors. These parts are hereinafter referred to as the "top subsection", with the cover plate, and the "bottom subsection", i.e. the bottom plate. Welded joints between the single partial cross-sections are impossible due to the small clear distance of only 170 mm between the external steel plates. Therefore, the shear connectors are welded to the cover and bottom plate alternately.
- The two subsections are joined together by endplates – such as the main girder webs of the trough bridge of this example – at the deck slab support lines, forming a steel box with internal perforated separators (shear connectors).
- Finally, the steel structure is filled with unreinforced standard concrete, the so-called core concrete, through concreting openings in one of the two endplates.

The assembly method for the SCSC plate described above outlines the main process sequence during prefabrication (see Fig. 2). Different cross-section types are possible by amending the offset between the shear connectors of the top and the bottom subsections. Hence, two specific cross-section types with shear connectors in extreme positions can be identified: a sandwich plate with evenly spaced shear connectors at a centre-to-centre spacing of 500 mm on the one hand and shear connector pairs just 60 mm apart on the other. Apart from their different constructional design, the main difference between the two types is the shear behaviour of the core concrete.

2.2 The load-carrying mechanisms of the SCSC plate

In principle, the main structure of the sandwich plate consists of the external steel plates (cover and bottom plates), the longitudinal shear connectors and the core concrete.

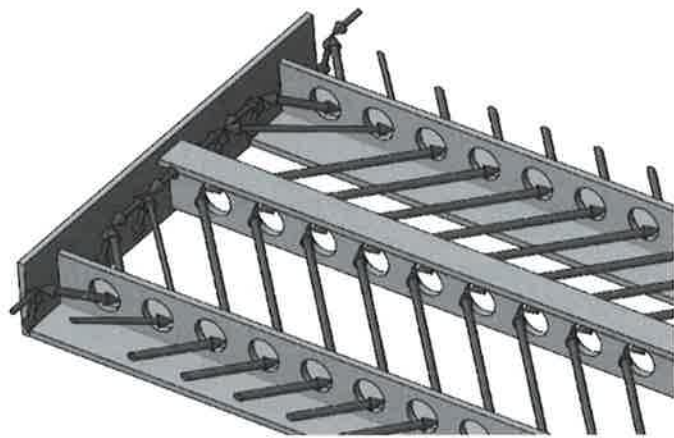


Fig. 3. Load-carrying mechanism of concrete strut model with 500 mm spacing between shear connectors (shear coupling mechanism only); axonometric view. Institute of Structural Engineering, TU Wien [2]

An intended load-carrying function is assigned to each component as a part of the whole complex engineering model.

The capacity to resist bending moments transverse to the bridge axis comes from the composite section (see Fig. 2, step 3), which consists of the external steel plates and the section part of the core concrete in the compression chord.

A shear-resistant coupling of the two subsections by welded joints between every longitudinal shear connector and both external steel plates would be the best structural solution. However, this is not possible because of the inaccessibility during fabrication. Consequently, the core concrete acts in conjunction with the longitudinal shear connectors as the shear coupling component of the SCSC plate. The shear connectors of each subsection transmit the shear forces resulting from the plate bending moment directly to the adjacent shear connectors of the other subsection via inclined horizontal compression struts in the core concrete. The load transfer in the strut support areas is performed by the cylindrical concrete discs (parts of the concrete core that fill the circular cut-outs in the shear connectors) as well as the front faces of the shear connector cut-outs. A complex multiaxial compression stress condition ensues in the concrete discs due to the aforementioned carrying mechanism according to plate bending, shear stress and local load distribution depending on the location within the sandwich structure (slab centre or support area) and the effect of friction in the interconnecting joint.

Fig. 3 shows the shear-coupling mechanism of sandwich plate type 1 schematically. For clarity, the cover plates of the subsections are shown only partially. The centre-to-centre spacing of the shear connectors is 500 mm. Furthermore, the core concrete is substituted by arrows that represent the horizontal compression struts. This type of shear connection between the two partial cross-sections can therefore be characterized as the “concrete strut model” (see also Fig. 2, cross-section type 1).

Cross-section type 2 (see Fig. 2) can be generated by shifting one subsection in the direction of the longitudinal axis of the bridge to reach a 40 mm minimum thickness (clear distance between two shear connectors) in the re-

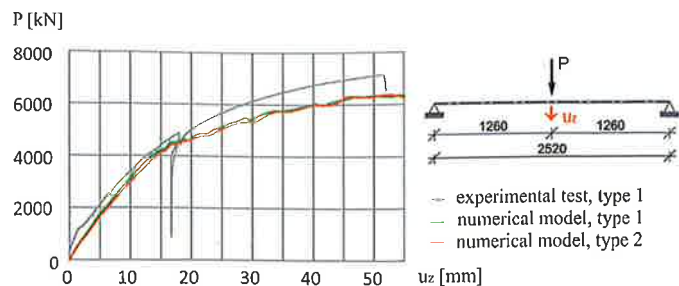


Fig. 4. Force-deflection diagram (P - u_z) diagram for an experimental test on a test specimen with cross-section type 1 and characteristic curves for numerical simulations (FEM) on sandwich structure models of the two cross-section types; structural system of SCSC plate test specimen with reduced span. Institute of Structural Engineering, TU Wien [2]

stricted concrete chambers. This value is derived from the core concrete composition, especially the flowability and the diameter of the largest grains. Thus, another shear force-carrying mechanism is generated by the change in the character of the cross-section (type 1 compared with type 2) in such a manner that adjacent concrete discs have a very short load path between the upper and lower longitudinal shear connectors. This modification has a direct impact on the plate stiffness and the stress-strain behaviour of the respective concrete discs. The aforementioned mechanism of shear connection is called the “concrete bolts connection”, see Fig. 2.

3 Initial investigations of the load-carrying behaviour of the sandwich plate under predominantly static loading

The sandwich structure was analysed at the Institute of Structural Engineering, TU Wien, during the preparation of project papers and master's and doctoral theses.

Extensive preliminary investigations of type 1 sandwich plate elements were carried out with a reduced span of 2520 mm loaded with a line load P at the plate span centre and considering several shear connector geometries. The results of these experimental carrying capacity studies presented in [1] have been extended by parameter analyses based on the finite element method (Abaqus/SIMULIA [13]), see Fig. 4.

Summarizing the investigations of sandwich plate elements with a reduced span corresponding to [1], in principle, both the function and the carrying capacity of the SCSC plate with longitudinal shear connectors were confirmed. However, the findings of the investigations made it clear that the conditions for the use of existing design models for concrete are not applicable owing to the construction method of the sandwich plate as well as the shear connector geometry. In particular, the influence of the interaction between the core concrete and the longitudinal shear connectors required additional considerations.

3.1 Cross-section types

In conjunction with the conclusions of type 1 sandwich elements, complementary non-linear numerical simulations were carried out on SCSC models with cross-section

Table 1. Description of different types of shear test specimen

Specimen set name	Specimen No.	Cross-section type and centre-to-centre spacing	Design features
T1a	1 – 3	type 1: 500 × 500 mm	Basic specimen type comparable with specifications to [1]
T1b	4 – 6	type 1: 500 × 500 mm	Design corresponding to set T1a, partitions of the core concrete in the edge regions of the specimens were replaced by styrofoam inlays in order to isolate the emergence of concrete compression struts from other possible unintended wedge effects
T2	7 – 9	type 2: 60 × 940 mm	Concrete chambers 40 mm and 920 mm thick

type 2. The system defaults were chosen depending on the dimensions as well as the support and symmetry conditions of type 1 models. Fig. 4 shows the comparison of the force–deflection diagram determined experimentally for a test specimen with cross-section type 1 and a characteristic graph of the post-test numerical simulation of a type 1 model according to [1] and the result of a comparative calculation for a type 2 model.

The force–deflection diagram of test specimen type 1 presented shows a nearly linear elastic initial stiffness that is sufficiently well reproduced by the corresponding numerical calculation. Several planned retention times during the experimental procedure appear as decreases in the applied load in the curve. The unloading and reloading loop at a deflection of about 18 mm was due to test-related reasons. Furthermore, there is a very ductile structural response in the upper load ranges. The ultimate failure of the test specimen (overall depth: 200 mm; cover and bottom plate: 20 mm thick; longitudinal shear connectors: 20 mm thick, 100 mm dia. cut-outs) by concrete fracture occurred at a test load of about 7000 kN.

In order to improve the consistency between the results of the numerical calculations and the measurement results of the experimental laboratory tests in the upper load areas, the input parameters of the material model used for concrete, CDP (concrete damaged plasticity model), were modified. Within the CDP model, the definition of compressive and tensile material behaviour can be defined separately with an extension to damage parameters for both compression and tension. The concrete compression stress–strain graph according to Eurocode 2 [9] was expanded beyond the nominal ultimate strain accord-

ing to [3]. This extension was necessary due to the high crushing strains that are likely to occur within the concrete disc areas. In addition, the impact of the system variables on the failure criteria according to Drucker-Prager was examined by a parameter analysis. Shear tests on representative sandwich plate specimens were planned and implemented in order to verify the confirmation of the newly established FE input data accuracy and study the differences in the load-carrying behaviour of the cross-section types.

3.2 Experimental determination of shear capacity

The experimental programme comprised three test series with a total of nine test specimens to evaluate the shear capacity as well as the deformation behaviour of only one single concrete disc. The tests were performed in the first half of 2015 at the laboratory of the Institute of Structural Engineering, TU Wien. The experimental investigation was expected to supply insights into the difference in the shear strength of sandwich plates with cross-section types 1 and 2 as well as a more detailed understanding of the stress condition, deformation and crack behaviour of the core concrete and the formation of the concrete compression struts.

The shear test setup and the main findings gained from the test results are described below in detail.

3.2.1 Test setup

Owing to the special composite design of the SCSC plate, particular requirements for the test specimens for shear

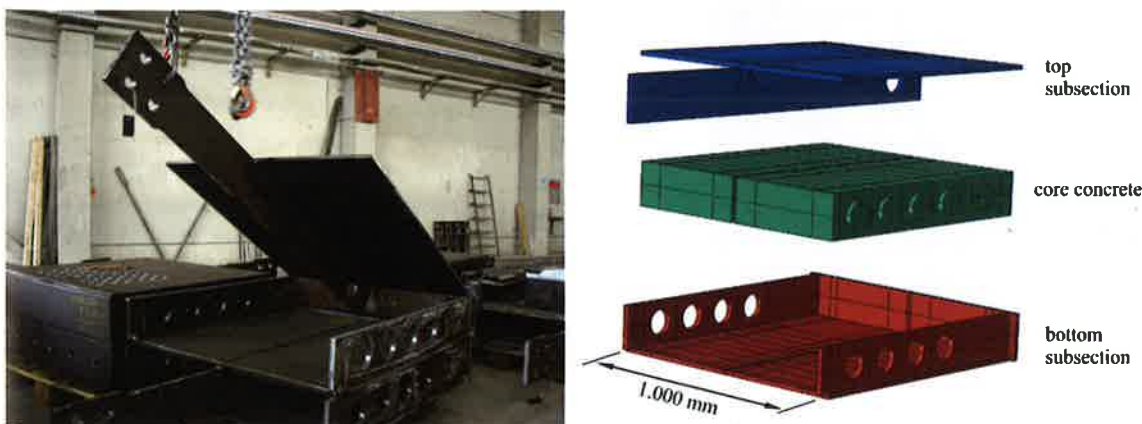


Fig. 5. Steel subsections during assembly and schematic exploded view of a shear test specimen (T1 specimen shown as an example). Institute of Structural Engineering, TU Wien

tests were taken into account because standard push-out test specimens could not be used. Small adapted sandwich plate sections have been demonstrated to be suitable as shear test specimens.

The following considerations affected the structural design of the shear test specimens in a significant manner:

- The compression struts in the core concrete which are responsible for the transfer of the longitudinal shear forces in the sandwich plate lead to a specific stress-strain behaviour in the concrete discs. This complex multiaxial state of stress can only be adequately simulated in a laboratory test by re-creating the geometry conditions of the real plate structure itself. Therefore, the width of the test specimen was set to 1 m (see Fig. 5), which means a plate strip of two concrete chambers.
- The test specimens were sections cut out from the real sandwich structure (see Fig. 5); the simulation of the given boundary values and conditions was precisely planned and realized.

A brief overview on the different shear test specimen types is shown in Table 1.

Fig. 5 shows a schematic drawing of the shear test specimens and the corresponding drawing of steel sections during fabrication (T1 specimens for experimental studies are shown here as an example). Each test specimen consisted out of two partial steel sections of steel grade S355 [10]. The partial steel sections consisted of a top subsection (blue) made from a 15 mm thick cover plate that was welded to an "internal" shear connector (20 mm thick) with one single circular 100 mm dia. cut-out, and a bottom subsection (red) where the 15 mm thick bottom plate was connected to two lateral shear connectors (20 mm thick with 3–5 circular cut-outs depending on specimen set type) and completed by an end plate made from 20 mm thick steel plate. The steel parts were braced together during the concreting by a temporary auxiliary structure; in the finished state there was no structural connection (such as welded joints, bolted connections, etc.) between the two subsections except the hardened



Fig. 6. T1a specimen installed in the shear test facility, with black and white coloured observation fields on the cover plate for optical measurements, hydraulic presses and load cells. Mechanism of forces acting shown by arrows (blue: displacement-controlled load input; green: reaction forces). Institute of Structural Engineering, TU Wien

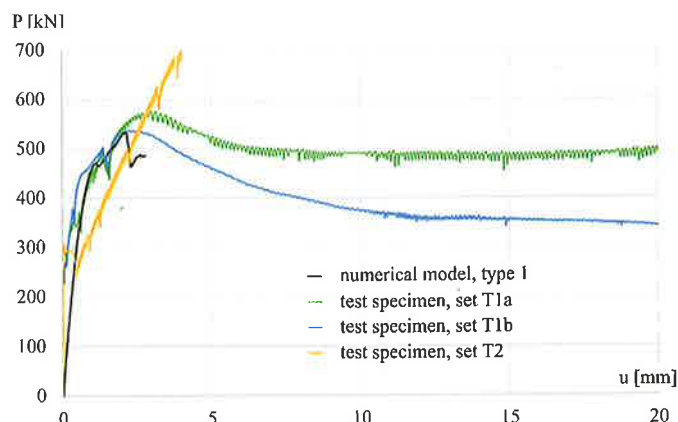


Fig. 7. Selected load-deformation (P - u) diagrams for T1 specimens compared with the result of a corresponding numerical model and the characteristic diagram for a T2 specimen. Institute of Structural Engineering, TU Wien

core concrete (green, 170 mm thick). The test specimens were filled with normal concrete of strength class C 30/37 according to Eurocode 2 [9] with high flowability and a maximum grain size of 8 mm.

One cover plate in each specimen set was produced with holes on a defined grid in the area of the circular cut-out of the internal shear connector to evaluate the mutual displacement between the core concrete and the top subsection and to investigate cracks in the concrete during the experimental procedure. The measuring concept covered comprehensive force measurements via 12 load cells. Strain and displacement measurements of the cover plate and the core concrete surface were measured by an optical 3D deformation analysis in the area of the internal concrete disc. Comparative strain gauge measurements were also performed. Displacements (both relative and absolute) were recorded by linear potentiometers and inductive displacement transducers.

The shear test specimens were installed separately in the test facility in the horizontal position. Both the external concrete discs and the lateral shear connectors of the lower subsection were secured against horizontal movement. An equivalent axle load was applied by means of four vertical hydraulic presses, as shown in Fig. 6.

The displacement-controlled tests were performed with a constant displacement rate of 0.2 mm/min, whereby the top subsection was pulled out of the test specimen parallel to the system axis of the internal shear connector.

3.2.2 Selected test results

The analysis of the shear test series, separated according to the different cross-section types, is explained below.

All characteristic diagrams show a highly stiff response in the lower load range (see Fig. 7). Looking at the load-deformation behaviour of T1 specimens, a decrease in stiffness can be identified due to the occurrence of plastic deformations as well as micro-cracks in the core concrete; failure occurred by shearing between the internal concrete disc and the surrounding core concrete on one or both sides. Both the load-deformation behaviour and the failure mode of T1 specimens were mapped adequately by

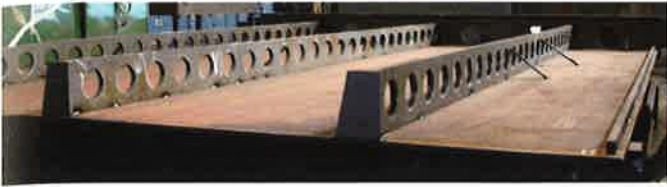


Fig. 8. Partial cross-section of a sandwich plate specimen with a span of 4080 mm during fabrication. It comprises three 20 mm thick cellular longitudinal shear connectors attached to one 15 mm thick external steel plate with spot welds, end stiffeners and one endplate with round concreting openings. Institute of Structural Engineering, TU Wien

the numerical calculation (see Fig. 7). This numerical analysis was performed on the basis of adapted input parameters for the materials steel and concrete. A change in the shear-carrying mechanism of T1 specimens appeared after exceeding the maximum load: The continuous force reduction goes hand in hand with a pronounced sliding mechanism in the existing shear planes as well as a force rearrangement from the inclined horizontal compression struts to emerging compression struts perpendicular to the circular square sections of the concrete discs. This behaviour can be explained as an almost ideal plastic system response. Here, a significant difference of nearly 25 % in the level of the sliding plateaus can be observed based on wedge effects inside the core concrete of T1a specimens, which is reflected by an excessive force value in comparison to the force value of T1b specimens with styrofoam inlays.

Each T2 specimen possessed a high initial stiffness up to the ultimate load of approximate 300 kN. The shearing of the internal concrete disc on the side of the broad concrete chamber as well as a cleavage fracture in the restricted concrete chamber due to an extremely high multi-axial state of stress in the area of the internal concrete disc appeared as the failure mechanisms here. The subsequent shape of the diagram is exclusively due to restraint effects affecting the sandwich elements in the testing frame. The test was cancelled at a test load of 700 kN due to the fact,

that no significant change in the carrying behaviour beside the mentioned restraint effects was observed.

Additional evaluations, especially due to the opening of the test specimens after completion of the tests, provided valuable information on the crack patterns in the core concrete.

4 Accompanying and future research topics

This section provides a brief overview of completed large-scale laboratory tests under predominantly static loading as well as future investigations on the issue of the SCSC plate.

Experimental load capacity tests on SCSC plate elements with a span of 4080 mm in accordance with the dimensions of the typical trough bridge deck slab (as shown in Figs. 1 and 8) under predominantly static loading were performed at the premises of LKI Graz (Laboratory for Structural Engineering, Graz University of Technology) in the first quarter of 2016. The system width of the test specimens was set at 3000 mm.

The test facility – representing an adapted and reversed “three-point bending test” – is shown in Fig. 9. The test specimen was installed supported by bearing pedestals that were prestressed against the strong floor of the laboratory by threaded rods. The load application was realized by water-filled pressure pads, covering a load area of 3×3 m. In addition, numerical calculations were carried out on the basis of the adapted input parameters. The results of this FE analysis showed a good correlation with the measurement values of the experimental static load capacity tests on SCSC plate elements.

Further investigations on the sandwich plate focus on the experimental determination of the fatigue strength, supported by accompanying numerical analyses. This research package basically includes the definition of non-standardised notch types of the SCSC plate design details, in particular the holes in the longitudinal shear connectors.

5 Conclusions

Experimental laboratory shear tests on composite test specimens in three different configurations were performed at the Institute of Structural Engineering, TU Wien. The measurement results provided valuable findings in relation to the carrying capacity and the distortion behaviour of the whole core concrete as well as single concrete discs. In addition, guide values for the input parameters of the material models for steel and concrete were detected by extensive comparative numerical simulations.

In conclusion, it can be stated that the structural model in the mean of concrete compression struts as shear transferring component [1] was proven by the results of the experimental shear tests. Fundamental data of the core concrete behaviour in the case of shear load act as an extensive basis knowledge for further investigations on the SCSC plate (see Section 4). Here in particular, information on the stress condition in a concrete disc, the shear strength values as well as slip values in the interconnecting joint between steel and concrete, and the failure mechanism of the core concrete due to shear forces is gained.

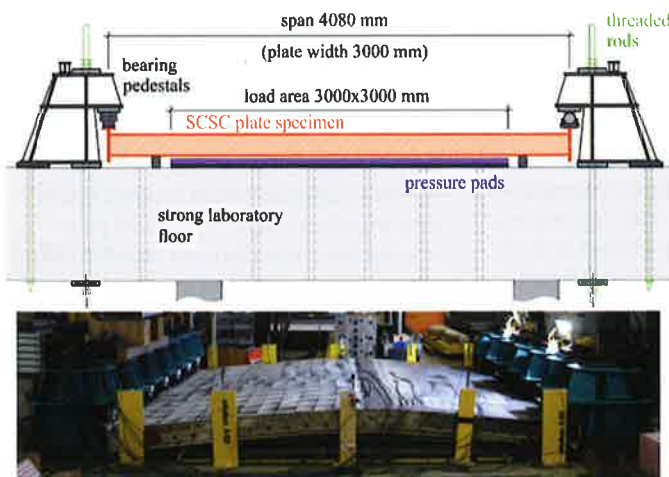


Fig. 9. Test setup for static load-carrying investigation with type 1 specimen installed. Longitudinal section and view of testing area during experimental procedure at maximum test load. Institute of Structural Engineering, TU Wien

Acknowledgements

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Symbol list

- P Test load [kN]
 u_z Vertical deflection at mid span of SCSC plate test specimens with reduced span [mm]
 u Horizontal deformation of the internal shear connector of the SCSC shear test specimens [mm]

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Keywords: sandwich plate; SCSC plate; longitudinal shear connectors; railway bridges

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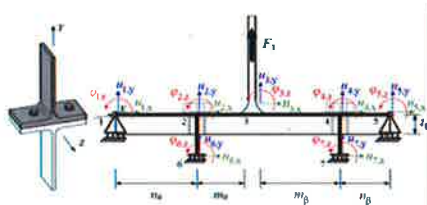
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Completed Phd theses

Fire resistance of cold-formed steel columns

The research addresses the study of asymmetric T-stub components subjected to tensile loads, through analytical, numerical and experimental approaches, defined in the case of bolted moment end plate connections with asymmetry conditions. The main objective is to calculate the properties of strength and stiffness, and compare them with symmetric components. The behaviour of the component was characterized through an equivalent matrix model, and the internal forces calcu-

lated were used to evaluate the ultimate resistance and the stiffness. Values obtained were compared with experimental results from tests developed in both symmetric and asymmetric configurations. The model fits to the experiments



Analytical frame model

with allowable precision. Finite elements simulations from models tested and from beam-to-column end plate connections were carried out also, in order to study additional parameters to estimate the suitability of the component proposed to the global behaviour of the connection.

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