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Composite Sandwich Footbridge – Numerical ESL FEM Calculations vs. *In Situ* Measurements

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Selected results of the static analysis of composite sandwich footbridge with the corresponding *in situ* measured values are compared in the paper. The analysed bridge is a research object, which was built in 2015 and is currently located at the Gdańsk University of Technology campus. Since it is a novel structure, a proper definition of the bridge numerical model, allowing its safe design, is very important. Therefore, instead of some preliminary research, carried out on sandwich beams or the bridge segment, also the calculated structural properties of the full scale object should match the experimentally predicted response. This verification was required to obtain permission for the bridge exploitation, according to the government regulations.

Key words: layered structures, polymer-matrix composites, footbridge, finite element analysis, *in situ* test.

1. Introduction

The considered footbridge (see Fig. 1) is a novel structure created in 2015 by consortium: Gdańsk University of Technology, Military University of Technology and Roma Private Limited Company (headquarters in Grabowiec, Poland), as a research object in the FOBRIDGE project, cofinanced by the National Centre for Research and Development (grant PBS/B2/6/2013) (see [1]). The aim of the grant was to elaborate material and structural design of the footbridge made of composite sandwich panels. The following aspects were considered among the project: architectural considerations, materials selection and identification of their parameters, development of production technology and wide numerical analyses of the structure's static and dynamic responses, additionally supplemented by extensive experimental investigations. The experimental tests were

Fig. 1. Overall view of the footbridge located at the Gdańsk University of Technology campus.

performed using models at different levels of their complexity. They comprised preliminary research carried out on laminate coupons, sandwich beams [2] or 3 m long bridge segment [3], as well as the final full scale load tests [4, 5]. The obtained results allowed for a proper validation of numerical models, which is very important in the case of a novel material and technology applications. The final footbridge tests were an additional verification, which is required to obtain permission for the bridge exploitation, according to the government regulations.

The paper includes the comparison of selected results of the numerical static analyzes with the corresponding ones, measured during the full scale *in situ* load tests.

2. Footbridge description

The footbridge is a simply supported, low elevation arch, U-shape cross section structure. Its basic dimensions are: 14 m span length, 97.4 m vertical radius, 2.6 m deck width and 1.3 m wall height. The bridge has a relatively low construction depth (distance between the soffit of the bridge and the top surface of the foot/cycle path), it is only 11 cm.

The bridge is a multi-layered sandwich structure. The outer skins are made of laminated polymer composites, comprising of stitched and balanced BAT [0/90] and GBX [45/–45] E-glass fabrics (reinforcement) and flame retardant vinylester resin (matrix). A 100 mm foam core, having a density of 100 kg/m^3, is applied between the skins. The basic single skin ply stack is [BAT/GBX/BAT/BAT/GBX/BAT] (only load bearing layers are included). The laminated parapets are formed by outer skins extension and folding. Their structure is strengthened by two layers of BAT fabrics. The structure is complemented by transverse and longitudinal ribs made of CSM300 and GFRP precast stiffening elements in the supporting areas. Total mass of the footbridge is 3.2 tones. The whole structure is manufactured using the infusion technology in a single production cycle [4].

3. Full scale load tests

The full scale load tests were performed in May 2015. The footbridge was loaded two times, tests denoted as U1 and U2. The ballast was adopted to induce effect close to maximum characteristic design live load, taking into account middle span bending moment. Additionally, third test (denoted as U3) was launched in September 2015. Its aim was to load the bridge up to its design limits, corresponding with ultimate limit state. In all the above mentioned cases, the load was applied to the footbridge via concrete slabs (see Fig. 2). In order to check the spatial behaviour of the structure, each quarter of the deck in U1 and half of the deck in U2-U3, was loaded in subsequent steps. The total weight of concrete slabs, which were put on the deck, was 140 kN in U1-U2 and 201.8 kN in U3.

Fig. 2. Footbridge loaded during tests U1 (left side) and U3 (right side).

A number of 117 independent measurement points were installed on the footbridge to monitor its behaviour. The system includes 36 strain, 57 displacement, 4 elastomeric bearings strain, 4 support settlement and 16 temperature measurement points. The points were located in 5 cross sections (0L, 1/4L, 1/2L, 3/4L, 1L). It is worth to mention that various techniques were used to analyse behaviour of the structure. For instance three strain measure techniques where used for points in the mid-span, where the highest strain values were expected (strain gauges SG, fiber brag grating strain sensors FBG, vibrating wire strain gauges VWSG).

The example location of strain and displacement points in the mid-span section is shown in Fig. 3.

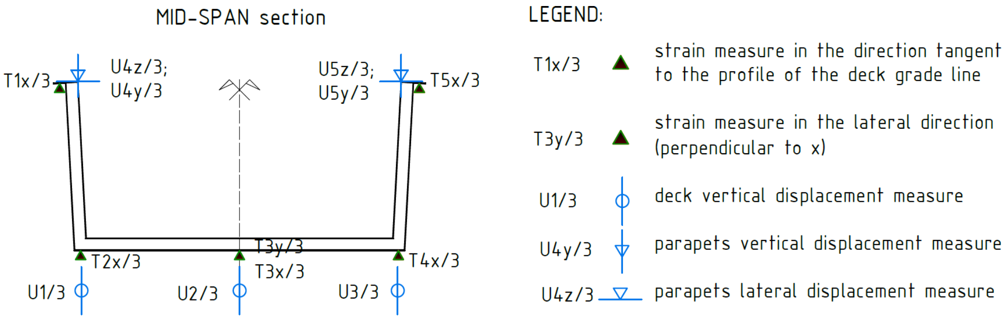

FIG. 3. Location of measurement points in mid-span section of the footbridge.

4. NUMERICAL ANALYSIS

Static linear calculations are performed using ABAQUS 6.14-2 FEM code. A numerical model comprising only of shell finite elements is created, since the thickness of the cross section elements is small as compared with the span length. This is a one of many possible methods of the sandwich structure numerical modelling, regarding recreation of its static mechanical behaviour. Equivalent Single Layer technique and First Order Shear Deformation kinematics (see e.g. [5–8]) are used to describe the behaviour of the footbridge. The mesh of finite elements comprises of 86 671 nodes and 84 236 S4 elements (see Fig. 4). It is very fine, thus the discussion about the mesh convergence is avoided.

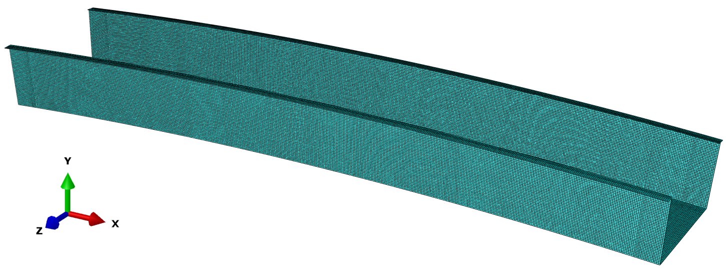

FIG. 4. Visualization of FEM model.

The layers of laminated composites are modelled using plane stress, elastic, orthotropic material law, while the foam is treated as an elastic isotropic continuum. The foam core is a one layer of the full stacking sequence similarly. The following layer sequence [BAT/GBX/BAT/BAT/GBX/BAT/FOAM/BAT/GBX/BAT/BAT/GBX/BAT] is applied as the basic one in the analysed bridge.

The chosen approach allows to analyse the global bridge behaviour using a simple and easily available method of sandwich composite structures mechanics description and hence provide accurate results in the shorter possible time. The precise solutions in a foam core or in local concentrated action zones is not verified here. In order to analyse local influences, a model can be used in which the laminate skins are made of multi-layered shells and the foam core is divided in the thickness direction using brick elements.

5. FEM calculations vs. *in situ* measurements

The numerical results in the selected, representative points in the footbridge mid-span are compared here with the measured *in situ* ones. All presented results refer to the first performed test denoted as U1. The comparison of calculated and measured static displacements in the middle of the deck, see U2/3 point in Fig. 3, are shown in Fig. 5. The longitudinal strains in the point located in footbridge parapet, see T1x/3 point in Fig. 3, are illustrated in Fig. 6.

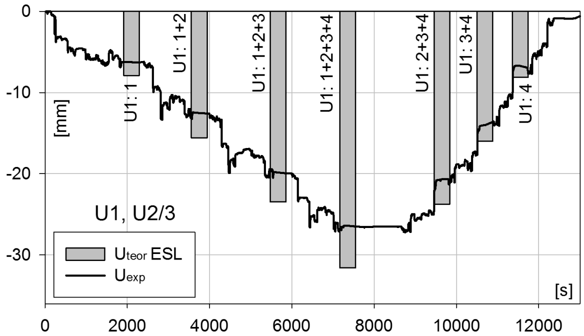

Fig. 5. Calculated and measured values of displacements in point U2/3 during different stages of test U1.

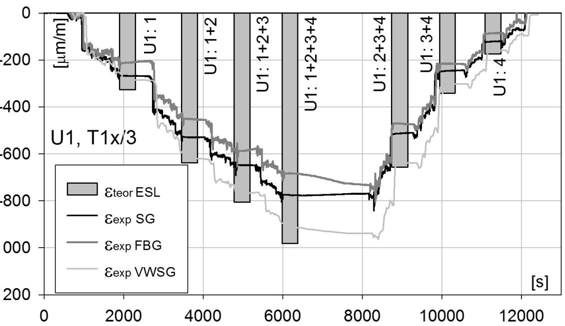

Fig. 6. Calculated and measured values of longitudinal strains in T1x/3 during different stages of test U1.

6. Final remarks

The results of static analysis of the bridge described in this work correspond quite well with the experimentally measured values. The numerically predicted bridge response under static load is slightly overestimated. This may be attributed to the environmental conditions, e.g. temperature, which may affect elastic properties of the materials. Nevertheless, it means that all the global design variables and assumptions, allow creation of a safe structural solution. However, it is recalled that a careful attention needs to be paid in the areas of highly local influences during the design.

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