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Evaluation of static strength and stress-strain analyses of a realistic full-scale model of a GRP railway freight bogie

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Abstract: The paper describes results of an experimental programme carried out as one of the essential phases of the implementation of a EUREKA project EUROBOGIE, which is aimed at development of advanced vehicle bogies and has a great potential to lead to more efficient movement of freight and passengers with lower environmental impact. The aim of the project is to evolve the use of fibre reinforced plastics in rail bogies and demonstrate the advantages of using such materials. The bogie consists of three main load carrying parts, namely two quite massive side beams connected by a central transom plate which are manufactured in a single moulding operation using the RTM method. One of the critical issues in the design and manufacture is the connection area of the transom with the side frames. Therefore, testing of this subcomponent, as well as experimental evaluation of strains predicted by finite element analysis was an important part of the bogie development. After fixation of the full-scale subcomponent model, static load was applied to failure, which occurred at 188 kN and 295 kN respectively, and strain values at critical nodes were recorded. The experimental programme confirmed not only the feasibility of the component design and manufacturing process, but also a very good quality from the viewpoint of the component strength and manufacturing parameters including the RTM process. It was also found that strain irregularities corresponded to latent internal material defects.

Keywords: Composite structures; Manufacturing; Experimental mechanics; Railway bogie.

1. Introduction

The paper deals with results of work carried out as one of the essential phases of the implementation of a EUREKA project EUROBOGIE which is aimed at development of advanced vehicle bogies. The advanced designs utilise the intrinsic properties of fibre reinforced plastics such as high working strains and internal damping, low density and good fatigue performance [1-3]. The GRP bogie has been designed for high speed freight vehicles whose upper and lower frames act as the suspension. Innovative aspects of the designs include lateral compliance to facilitate

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wheel sets going around curves without steering, reductions in noise and vibration, lower track forces and functional integration of components.

The bogie consists of three main load carrying parts, namely two quite massive side beams connected by central transom which are manufactured in a single moulding operation using the RTM (resin transfer moulding) method – Fig.1a,b. One of the critical issues in the design and manufacture is the connection area of the transom with the side frames. A special procedure of glass fibre lay-up in the connecting area was designed and several components were moulded. This is a very difficult task due to the size of frame 2.5 x 2.5 m and its thickness (up to 120mm). The manufacture RTM process, which, in general, recently has got under high level of control [4], can result in high exothermic reactions due to the poor thermal conductivity of the resin or insufficient wet-out leading to a deterioration in the final mechanical strength and fatigue properties [5-7]. Therefore, testing of subcomponents with detailed experimental stress analyses, in connection with computations of critical stresses, is an important part of the bogie development, verifying measured strains and those predicted by finite element analysis. It also can be pointed out that both the results of calculations and experimental verification are essential documents for a future certification process with European railway Offices.

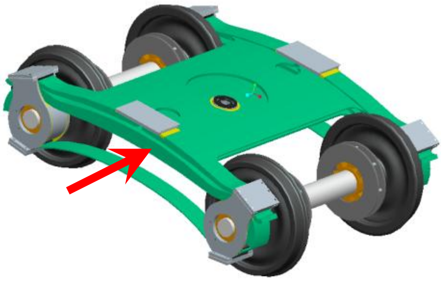

Fig. 1a. Scheme of GRP railway bogie, the massive side beam indicated by the arrow

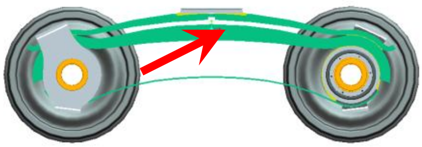

Fig. 1b. Side view of the bogie, the main massive side beam indicated by the arrow

2. Manufacture of T-piece as an experimental model

The critical part of the bogie from the viewpoint of design and manufacture is the connection area of the horizontal transom plate with the side frames, carrying the main vertical loads. A special procedure of glass fibre lay-up in the connecting area was designed. A scheme of the glass fibre lay-up, manufactured as a single fabrics to be fixed in the mould before the transfer resin process starts, more exactly the model sub-component after the manufacture, is shown in Fig.2.

It can bee seen in Fig.2 that the lay-up of the glass fibre layers in the transom plate is 0/90^{o}, whereas the lay-up in the side beams is more complicated, as this part is not only carrying the vertical forces, but also transfer horizontal forces arising e.g. during braking, pushing etc. It is therefore impossible that the orientation of the fibres in this side beam is only longitudinal, though such the orientation would be the most suitable concerning the bending vertical loading. The fibre lay-up in the T-piece therefore represents a compromise. The lilac colour in Fig.2 indicates the pure longitudinal arrangement of fibres, whereas the red colour shows the area of the $0/90^{o}$ orientation.

The main dimensions of the T-piece – length of the side beam 1000 mm, length and width of the transom part 500 mm and 900 mm, respectively – are shown in Fig.2. The cross section of the side beam was 200 x 155 mm, the thickness of the transom part (dimension in z-direction) was 55 mm.

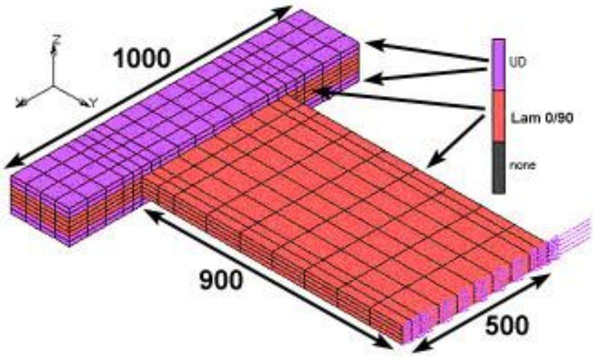

Fig. 2. Scheme of glass fibre lay-up in the experimental model of the side beam and transom

3. Computation of stresses and strains

Stress-strain state was calculated using finite element method (FEM). MSC-MARC finite element software was used, which correctly calculates the anisotropic properties of fibre composites and varying boundary and contact conditions. Computations were carried out at the University of Reading.

The material constants used in the FE model for the unidirectional material were: E11 = 37 GPa, E22 = E33 = 10 GPa, ν12 = 0.25, ν23 = ν13 = 0.05, and G12 = C23 = G13 = 4.3 GPa. The material constants for stitch-bonded fabric were: E11 = E22 = 12.6 GPa, E33 = 10 GPa, ν12 = 0.52, ν23 = ν13 = 0.17, G12 = G23 = 7.2 and G13 = 4.3 GPa.

The calculations were made at the following marginal conditions: (i) the side beam fully fixed against movement at any of the directions – displacement in the x-direction and rotation in the x-y plane and (ii) loading in the x-direction, at the corner opposite to the side beam – five thin arrows in Fig.2.

4. Experimental stress-strain evaluation

Since static test to failure was intended to be a part of the experimental programme and expected maximum loads were more than 300 kN, it was necessary to consider a suitable test facility with a sufficient load capacity. It was eventually decided to attach the T-piece to the SCHENCK PBVH machine, with 300 kN of the basic capacity, however more than 1600 kN with the load multiplier.

The only design and manufacture problem with the multiplier was the necessity to attach the specimen with a special inclined angle to ensure the adequate attachment and equal marginal and loading conditions as those used in the calculations.

Examples of the preparation works are shown in Figs.3 and 4. Fig.3 shows works during the attachment of the load multiplier, the attached T-piece is documented in Fig.4.

Fig. 3. SCHENCK PBVH machine being equipped with load multiplier

Fig. 4. Attachment of the GRP T-piece to the machine using the specially designed and manufactured gear

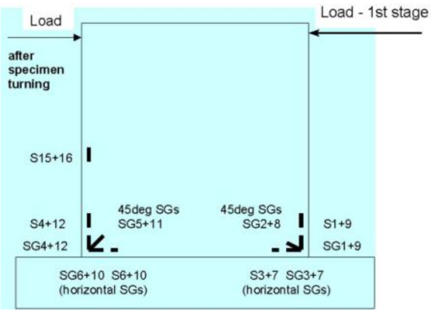

Fig. 5. Scheme of position and numbering of strain gauges

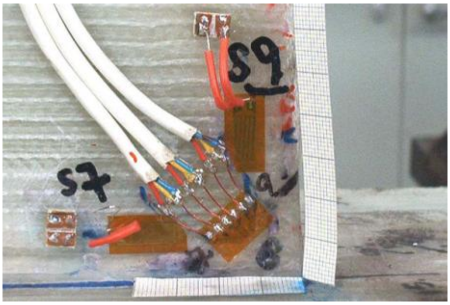

Fig. 6. Actual strain gauge rosette with auxiliary gauges at the corner of the transom part near the side beam

The experimental model – the T-piece was equipped with a system of strain gauges (SGs) at areas of predicted critical stresses, which were in the transom part near the corners near the side beam. Numbering of strain gauging with their schematic position is shown in Fig.5, where always two SGs belong to each of the positions. It means that one SG is bonded on the front side and the second one on the back side, symmetrically to the first one. Actual strain gauge rosettes with auxiliary strain gauges and their position are documented in Fig.6.

According to Fig.5, the loading was horizontal, which corresponded to the x-axis direction in Fig.2. In the first step, the loading direction was from one side, where e.g. SGs 1 and 9 where bonded ("vertical" gauges in Fig.5). After the failure, the T-piece was turned by 180^{o} and the same static test was performed from the other side, where e.g. "vertical" SGs 4 and 12 were bonded.

During static tests, strain values were automatically recorded using the Hottinger-Baldwin Messtechnik UPM60 device with a computer controlled data recording.

5. Results and discussion

5.1. Results of finite element analysis

Results of the most critical stresses in the y-axis direction ("vertical" in Figs.5 and 6), calculated for the static loading 408 kN, are shown in Fig.7.

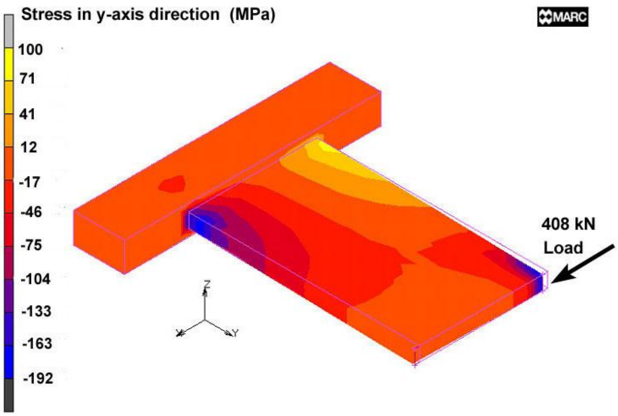

Fig. 7. Results of the most critical stresses in the T-piece in the y-axis direction

The FEM results indicated important information as follows:

- The area of the most critical stresses near the corners, where the transom part is connected with the side beam, corresponds to the distance of 80 – 100 mm from the side beam.
- For the loading applied according to Fig.7, compression stresses on the side opposite to the load (approximately 170 MPa) are higher than tension stresses on the loading side (approximately 100 MPa).
- Considering the E-modulus, maximum strain values at the compression and tension areas are 13492 μm/m and 7937 μm/m, respectively.
- Due to the stress concentration near the corners, failure could be predicted to occur at the sensitive area of the connection of the transom part to the side beam, either on tension or compression side.

Note that linear dependence of strain values on the load can be supposed in case of no internal damage.

5.2. Results of experimental strain analysis

Quite a lot of diagrams and data were obtained during the experimental evaluation of strains. Therefore, just the most important and critical data are presented and discussed in this section.

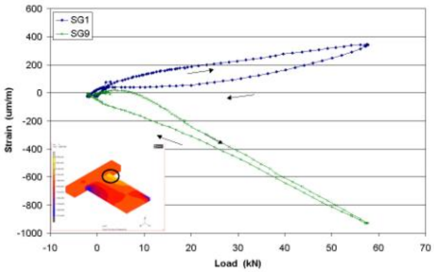

Fig. 8. Load-strain curves of "vertical" y-axis SGs 1 and 9 on the "tension" side during loading to 57 kN

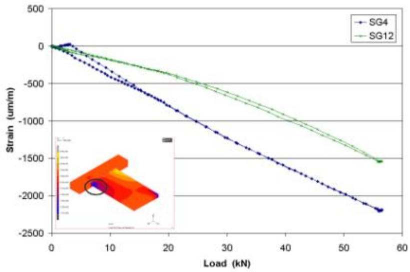

Fig. 9. Load-strain curves of "vertical" y-axis SGs 4 and 12 on the "compression" side during loading to 57 kN

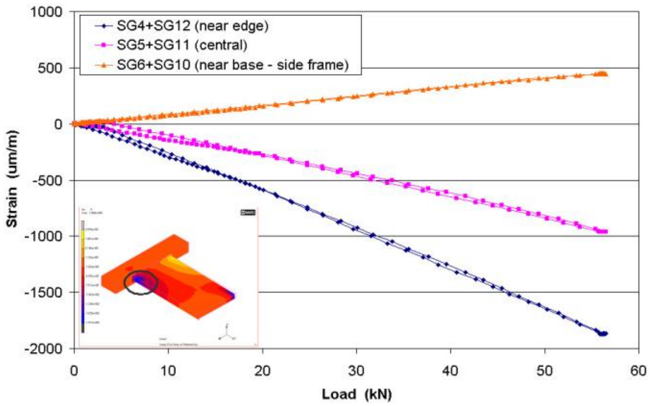

Fig. 10. Load-strain curves of all SGs on the "compression" side during loading to 57 kN, average values of symmetrical SGs are shown

Survey of selected tensile and compressive strains during the first loading step to 57 kN is shown in Figs.8 – 10, respectively. Note that unlike the compression side, where experimental values at the SGs 4 and 12 are more or less symmetrical (Fig.9), like they should be, values on the tension side of the corresponding couple of strain gauges, namely SGs 1 and 9 are asymmetrical and strange, particularly as regards the compressive strain at SG 9. Such the irregular behaviour likely indicates that the connection between the transom and side beam is not ideal in this area and some latent microstructure defects occur there. This hypothesis is in a good agreement with quite low maximum strength, just 188 kN, and failure in this problematic tension area – Fig.11. Note that effects of microstructure defects in GRP materials and components on both static and fatigue strength, as well as on strain distribution or even local self heating during fatigue loading is known [8,9].

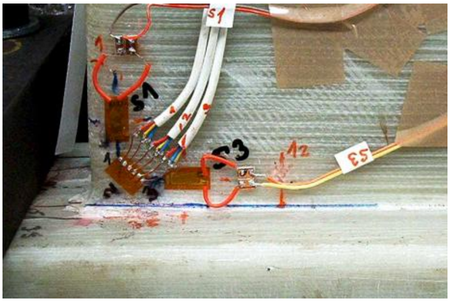

Fig. 11. First failure at 188 kN – crack along the connection between the transom and side beam in tension area

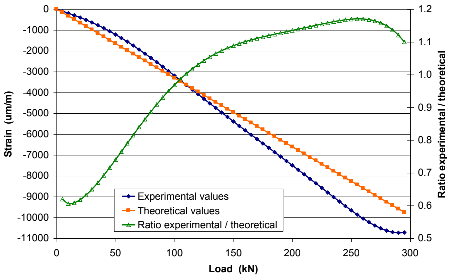

Fig. 12. Comparison of average values of compression strain at SGs 1+9 with theoretical values

Concerning the average values of the symmetrical SGs shown in Fig.10, the agreement with the calculated values is excellent. If the compression strain –13492 μm/m corresponds to the load 408 kN as mentioned in the Section 5.1., then –1885 μm/m corresponds to the load 57 kN. The actually measured average value in Fig.10 is –1875 μm/m, so the difference is less than 1%.

It can be seen in Fig.10 that the stress state near the connection of the transom to the side beam is complex, complicated. Though the "vertical" (Fig.5) stresses, either tensile or compressive affects the strength predominantly, the stresses in the 45^{o} direction are not negligible either and can contribute to the damage process.

After turning the specimen by 180^{o} in the attaching gear and loading from the opposite side, as indicated in Fig.5, the final strength was considerably higher, though the area of the SGs 1 and 9 was already damaged in tension. The maximum load was 295 kN in this case, which confirms that the area of SGs 4 and 12, loaded in tension at this step, was of a better quality. On the other hand, the low quality of the are near SGs 1 and 9, loaded in compression at this step, resulted in much worse agreement between theoretical and experimental values – Fig.12.

6. Conclusions

A comprehensive investigation programme of experimental strain analysis at critical points of a full-scale model of heavily loaded parts of railway bogie, made from glass reinforced polymer composite, namely connection of transom with side beam was carried out, following finite element analyses. The most important results of the experimental programme can be summarised as follows:

- In the first stage of static loading, when the area of likely material imperfections was located on the tension side, maximum strength exceeded 188 kN. After turning the specimen by 180^{o}, when a good material quality was on the tension side, the maximum static strength exceeded 295 kN load, though the opposite side was already partially damaged. Both the results of static strength were several times higher than the maximum required strength for the actual operating conditions.

- There was an excellent agreement between the calculated and measured strains before internal latent damage started to occur. In the areas of a not perfect material microstructure, actual values of strain analysis indicated internal material imperfections very distinctly.
- The experimental programme confirmed not only the feasibility of the component design, but also the feasibility of achieving a good quality from the viewpoint of component strength and manufacturing parameters used in the RTM process.

Acknowledgement

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