LIFETIME ASSESSMENT FOR GLASS-FIBER REINFORCED PLASTIC AUTOMOTIVE COMPONENTS

Razvan NATANAIL¹ and Dan-Maniu DUSE²

¹ Lucian Blaga University Sibiu, Manufacturing Department, Bd-ul Victoriei 10, 550024 Sibiu, Romania
² Lucian Blaga University Sibiu, Manufacturing Department, Bd-ul Victoriei 10, 550024 Sibiu, Romania
E-mail: razvan_natanail@yahoo.com; dan-maniu.duse@ulsibiuro.ro

ABSTRACT: The rapidly increasing use of glass fiber reinforced plastics (GFRP) in recent years has brought about the need for greater knowledge of their behavior under load. The objective of the present investigation is the experimental determination of the loading conditions for a GFRP roof of a six-door-stretch limousine and the application of the Nominal Stress Concept for determination of its lifetime to fracture.

KEY WORDS: Glass-fiber, GFRP, Nominal-Stress-Concept, fatigue, lifetime.

1 INTRODUCTION

The shortages regarding the development time for the realization of high performance and at the same time economical cars require reliable knowledge about the properties of the used materials. The continuing trend towards premium performance of modern cars has a significant increase in the mechanical and thermal load of components.

The assurance and maintenance of the safety and integrity of structures is one of the most important tasks in engineering. Numerous catastrophic failures that have occurred in the past have proved that this demand has to be given higher priority. An important reason for failures is the limitation of the actual knowledge (state of the art) in the field of strength of materials especially in the subject of fatigue.

The safety margin of a structure S is given by the comparison of the driving force B (loads, stresses, strains) and the resistance R (strength, toughness) of the structure:

\[ S = \frac{R}{B} \]  

Both properties are not of deterministic nature but very often extremely scattering, that means probabilistic distributed. Failures will occur when a high driving force meets with a low resistance.

The structural safety of car structures is directed to the overloading resistance (e.g. misuse, crash) and to the structural durability, figure 1. The failure - depending on the ductility - may be caused by normal stresses (brittle behaviour) or shear stresses (ductile behaviour). The component behaviour is not only determined by the material toughness but as well on the temperature, loading velocity and stress state. Some reasons for a decreased resistance are directionality, imperfections and unfavorable manufacturing influences.

The design concepts for the assessment of the structural durability are derived from the stress categories in structures:

- Primary membrane, bending and torsion stresses
- Secondary stresses (Structural stresses)
- Peak stresses or strains at notched regions
- Stress intensities near crack like defects.

The specific design principle of structures under variable amplitude loading is the idea of lightweight design which includes the higher load amplitudes to exceed the fatigue limit. The general outlay of the Nominal Stress Concept is shown in figure 2.

Figure 1. Structural safety of components (Issler)
The variable load or stress time function has to be classified with a counting method into a cumulative frequency diagram (CFD). The CFD gives the correlation of stress amplitude to the cumulative number of cycles.

The resistance is characterized by the component S-N-curve. The comparison of the spectrum and the S-N-curve and the application of a damage theory results in the damage sum for the given lifetime and finally in the lifetime estimation.

2 EXPERIMENTAL METHODS

An experimental stress analysis on a vehicle developed and modified by the company BINZ, the series Mercedes Benz E class (type W 212), was conducted. It is a six-door-stretch limousine, see figure 3. The roof of the vehicle is made out of glass-fiber reinforced plastic with +/-45° multi-axial layers. The connection of the roof frame was made with the also tested adhesives Powerbond and Sikaflex.

For the lifetime assessment the experimental stress analysis with strain gauges is the most suitable method. The test track should include typical but as well severe conditions to cover the driving habit of customers.

On the roof, strain gage rosettes were applied at a total of 7 points of measurement, see figure 4.
The application involves measuring locations relating to the right front side of the roof at the A-pillar, R1 and R6, the B-pillar, R2, the C-pillar, R3 and the D-pillar, R4. Also 0-45°-90°-DMS rosettes were applied in middle of the roof on the outer and inner side, R5 and R7.

The strain signals have been determined in extensive test runs in the area of Remstals, where a rough road was included. The measurement program covers following operating conditions: accelerate and full brake applications, reversing and full brake applications, cross tie (threshold crossing), drifting, city and countryside, rough road, slam of middle door, highway, driving over road curbs.

3 RESULTS

3.1 Service Conditions

The quantification of the loading-time-history is based on measurements during test drives were the strains are measured on distinguished spots of the structure.

The evaluation refers to the loading-time-history of the maximum principal stress at the individual measurement sites. An overview for all measurement locations and measuring rides is shown in figure 5.

The maximum stresses at the maneuvers are about 3 MPa. The window opening leads to the highest stress with mean values to 6 MPa, where the speed of the car is decisive. The influence of the speed is plotted in figure 6.

From the torsion stress history it can be concluded that the proportion of thrust is negligible.
3.2 Failure analysis of the GFRP

The operational strength analysis refers to the GFRP used for the roof. At the points of measurement a layered bending and membrane compression stress was found, see correlation of the stresses for the center of the roof in figure 7.

The counting methods are meant for transferring the load-time-history into a load - cumulative number of cycles-diagram (cumulative frequency diagram CFD). The counting methods are classified into single parameter methods with one result of counting (usually the amplitude) and two parameter methods with two results (usually maximum and minimum value).

The CFD is the result of the application of the different counting procedures to the load - time - cycle. The CFD contains illustrative information about the maximum load amplitude and (cumulative) number of cycles as well as the severity of the load spectrum (shape of the curve).

Figure 8 shows the determined collective of membrane stress for the center of the roof by using the Range Pair counting.

To simulate imperfections in the material, fatigue tests were carried out on notched specimens ($K_t = 2.5$). The material used for the fatigue study was in the form of laminated plates with +/-45° multi-axial layers. The samples have a top and bottom layer of 600 g/cm² of glass fiber and an epoxy resin system 285 of the firm Lange and Ritter. The rest of the specimen is filled with special filler with micro-balloons. The range of fiber volume fraction for the tested laminates was found to be 0.1. The top and bottom layers have a fiber volume ratio of 0.25. The shape and dimensions of the specimens used for the experiments are shown in figure 9.

Fatigue tension tests ($R = 0.1$) and fatigue tension-compression tests ($R = -1$) were carried out with a test frequency of 30 Hz, see comparison of S-N curves in figure 10. For the experimental determination of the S-N-curves, 6 specimens were tested on different load levels for each stress ratio till fracture.

The S-N-Curve ("Wöhler Line") is since decades the fundamental diagram for the fatigue design. The curve is valid for constant amplitude load cycles but is as well used to characterize the resistance for the damage accumulation theories under variable amplitude loading.

The comparison of the maximum compression stress amplitude of 1.5 MPa with the results of the fatigue tests, shows that the safety of the roof is very high, see the fatigue strength diagram of notched specimens in figure 11.
The results of the fatigue tests under bending loading with a stress ratio of $R = 0.1$ are plotted in figure 12.

An interaction diagram for combined bending ($R = 0.1$) and compression loading ($R = -\infty$) is shown in figure 13. This analysis shows that for the GFRP base material is no risk in the operation.

For assessing the durability of the bonding, fatigue tests under superimposed compression and bending load with a stress ratio of $R = 10$, have been carried out, see figure 15. The strain gage measurements carried out on the samples confirmed the ratio of bending stress to compressive membrane stress of 0.8 of operational stress for the fatigue tests, see figure 16.

### 3.3 Failure analysis of the adhesive bond

The similar analysis for the adhesive bond is based on the Range Pair spectrum of the measurements in figure 14. The maximum amplitude of the membrane stress is 1 MPa and the maximum bending amplitude is 0.8 MPa.
The S-N-curve of the combined compression bending tests on the samples is shown in figure 14. The fatigue strength is 0.94 MPa.

The damage caused by the loading cycle for a given lifetime is calculated based on the loading spectrum (driving force) and the S-N-curve (resistance), see figure 15. The operating strength calculation with the program WINLIFE (Steinbeis Transfer Center Transport Technology Ulm) results for the route of 61 km a damage sum of $7.89 \times 10^{-6}$. Therefore 126800 cycles and total 7.6 million km can be endured on the bonding at a critical damage sum of 1 to failure. A failure of the bonding under time variable loading is therefore no reason to fear.

4 CONCLUSIONS

Fatigue failures are still the main concern in engineering because of different reasons:

- The information about the loading history of the structure is not be exact enough known to the designer and depends very much on the customer
- All type of stress categories are contributing to the fatigue failure (effect of notches)

- The fatigue properties of materials and components are not readily available and will show often an extreme scattering
- Environmental effects will influence the fatigue strength and are often not investigated because of time and financial constraints
- The constitutive equations linking the component strength to the standard properties are often not exact enough known
- The fatigue fracture occurs in the macroscopic elastic range far below the static strength and without pre warning
- The concepts of structural durability are not fully and satisfactory developed, are not applied consequent in the practice and are not transferred according to the state of the art in an teaching of students and continuing education for engineers.

The application of the Nominal Stress Concept to variable amplitude loading is a powerful method for advanced lightweight design.

5 FURTHER RESEARCH

The structural safety of car structures is directed to the structural durability and to the overloading resistance (e.g. misuse, crash).

Further tests on GFRP doors are planned in comparison with steel doors. To simulate crash conditions, impact tests will be carried out on the doors, comparing the values with the results of static tests on the doors. A dynamic factor will be defined. Pros and cons of the GFRP parts will be determined in comparison with the steel parts.

A numerical calculation with the finite elements method (FEM) will be carried out for the GFRP components in comparison with the results of the static tests.

6 ACKNOWLEDGEMENTS

The research was carried out within the POSDRU/6/1.5/S/26 project, financed by the European Social Fund through the Operational Social Program Human Resources Development 2007-2013.

7 REFERENCES