EAN 2019
57th conference on experimental stress analysis

Experimental and FEM modelling for optimization of lightweight steel structures supported by fatigue tests of modern high strength structural steels

NOVÝ František[1,a] and PETRŮ Michal[1,b]

[1]Technical university of Liberec, Faculty of Mechanical Engineering, Studentská 2, 46117 Liberec, Czech Republic

[a]frantisek.novy@fstroj.uniza.sk, [b]michal.petru@tul.cz

Keywords: Optimization of lightweight structures, Fatigue, High strength structural steels

Abstract. Structural optimization has become very popular thanks to modern and powerful software tools. Nowadays a lot of various software for mechanical design and FEM analysis are available. Using those software tools some very nice lightweight structures can be design in fact, but in real practice there can be seen unexpected fatigue failures of those structures very often. This paper shows that optimization of modern lightweight structures using modern software tools can be done relatively easy but it also shows that optimization of lightweight structures which undergo cyclic loading should be in direct connection with fatigue testing of used materials. In this study, the optimization process of real lightweight structure (frame of the semitrailer) was supported by experimental determination of fatigue endurance, mechanical properties, microstructural and fractography analysis of used steels. Connection of structural optimization and detailed materials research resulted in successful and safety design of new lightweight frame of the semitrailer.

Introduction

The mass reduction, while maintaining the same or improving original performances, has become one of the most important goals of newly developed lightweight structures. The principle of lightweight structures design is based on mass reduction using optimization methods. Structural optimization deals with optimal design of load-carrying engineering structures and can be defined as the rational establishment of structural design that is the best of all possible design within a prescribed objective and given set of geometrical and/or behavioural limitations [1].

Various types of structural optimization methods can be used for mass reduction. Sizing, shape and topology optimization methods represent the three different approaches most frequently used in structural optimization. In a sizing optimization problem, the design model is fixed and the objective is to find the optimal dimensions of the structure. For a shape optimization problem, the aim is to optimize the structural shape without modifying the number of borders. Topology optimization allows to design a structure by seeking the optimal material layout within a given design space [2]. There is also fourth approach in optimization, based on application of new materials in design, which seems to be very easy but, it is the most problematic in fact.

In spite of the progress and development in materials science and technology, steel continues to be one of the basic structural materials. This is due to the potential of steel to be widely used in structures because of its low cost, good cold formability, high strength and high modulus of elasticity, as well as weldability. Designers have a great deal of grades of steels with different service properties at their disposal, from which they can select, depending on the demands on the structure being designed. Satisfying all technical and operational requirements is sometimes difficult, and even impossible. In transport machinery and equipment, including semitrailers, the operational conditions significantly affect their service life. The durability of structures operated during driving and carrying cargoes is associated with complex fatigue processes. This gives rise to the issue of not only the appropriate optimization of the part's design, but also the proper selection of its material in order to increase the operational reliability and durability.

Application of modern high strength structural steels allow us to design lightweight structures, but the risk of fatigue failure of modern lightweight structures manufactured from those steels is much higher in comparison with standard structural steels due to the lack of the knowledge about their fatigue behaviour. Due to the lack of the knowledge about fatigue behaviour of modern steels used for cyclically loaded lightweight structures a lot of unexpected failures of those structures can be seen in real practice [3].

Experimental materials

The materials characteristics of steels used in design of the newest lightweight semitrailers should be relatively high. For example, tensile yield strength of steels used for manufacturing of their chassis must not be lower than 600 MPa and the ultimate tensile strength must be above 700 MPa. Therefore two modern high strength structural steels namely STRENX 700MC and HARDOX 450 with improved yield strength were used for optimization in this study. A common S355J2 structural steel was taken in to consideration as a comparative steel.

STRENX 700 MC and HARDOX 450 are advanced high strength steels, designed to meet and exceed the high demands and standards of the vehicle industry. Developed specifically to address the challenges of transport and vehicle manufactures are used to save weight and/or to increase the payload. When using those steels, the transportation vehicles can be made with thinner steel while still retaining their strength properties. This reduces weight, allows for larger payloads, cuts costs and reduces the impact on the environment because less material is needed in production. A well known S355J2 structural steel has a ferritic pearlitic microstructure. The microstructure of STRENX 700MC steel consists of irregular ferrite with approximate average grain size of about 4 - 12 µm, with low amount of pearlite at the grain boundaries of ferritic grains and local occurrence of complex carbonitrides of titanium. The HARDOX 450 steel has microstructure of tempered martensite. Chemical composition and mechanical properties of STRENX and HARDOX steels in delivery state depend on the plate thickness. The detailed chemical composition and mechanical properties of tested steel plates with thickness of 10 mm are given in Tabs. 1, 2.

Table 1: Chemical composition of tested steels in weight %

S355J2								
C	Si	Mn	P	S	Cr	Ni	Cu	
0.18	0.03	1.47	0.015	0.011	0.03	0.02	0.04	
STRENX 700MC								
C	Si	Mn	P	S	Al	Nb	V	Ti
0.08	0.35	1.67	0.018	0.0037	0.015	0.06	0.014	0.015
HARDOX 450								
C	Si	Mn	P	S	Cr	Ni	Mo	B
0.20	0.39	0.80	0. 005	0.005	0.45	0.05	0.01	0.001

Table 2: Experimentally obtained mechanical properties of tested steels; average value from 5 measurements

Steel grade	Re [MPa]	Rm [MPa]	A_5 [%]	Z [%]
S355J2	376 ± 4	564 ± 6	28.1 ± 0.6	41.7 ± 0.9
STRENX 700MC	796 ± 3	849 ± 2	15.4 ± 0.2	36.1 ± 0.3
HARDOX 450	1425 ± 5	1560 ± 7	12.5 ± 0.3	38.0 ± 0.4

There are plenty of producers of high strength structural steels like: SSAB - Sweden, SWEBOR - Sweden, DUFERCO - USA/Brazil, ALGOMA STEEL - USA, ARCELOR MITTAL - USA, NUCOR - USA, HIGH STRENGTH PLATES AND PROFILES - Canada, NLMK - Europe, JFE STEEL - Japan, NSSMC - Japan, KOBE STEEL - Japan, TATA STEEL - India, ESSAR STEEL - India, CHAMPAK INDUSTRIES - India, RUUKKI - Finland, DILLINGER HUTTE - Germany, THYSSEN KRUPP - Germany, ILSENBURGER GROBBLECH - Germany, VOESTALPHINE GROBBLECH - Austria, ISD HUTA - Poland, ACRONI - Slovenia, BISALLOY - Australia, INDUSTEEL – ARCELOR MITTAL group. However none of them can guarantee fatigue properties or give any relevant information about fatigue behaviour of their products. They can guarantee only the chemical composition and basic mechanical properties, but fatigue properties are without any guarantee. Every of above listed producers declares quality of produced steel by newest production technology and everywhere is written that they are selling a high quality steel. What a nice guarantee, isn't it? The real quality of some sheets from S700MC steel on the steel market is depicted in Fig. 1.

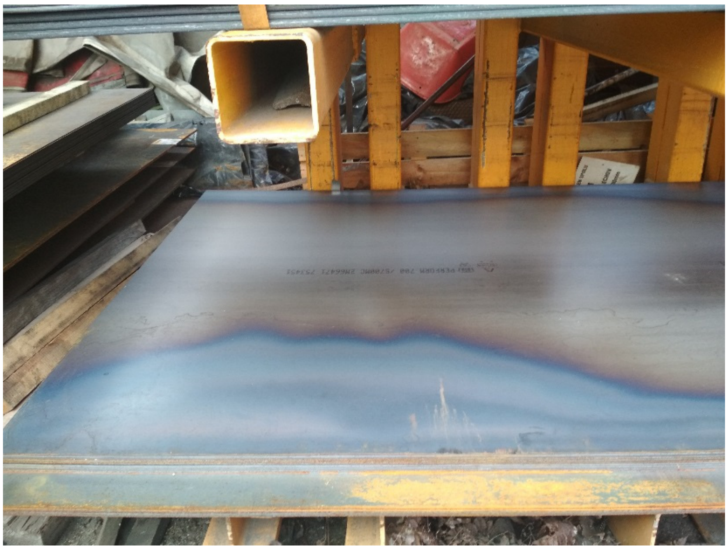

Fig. 1: Real (terrible) quality of some sheets from S700MC steel on the steel market; strong heat affection along edges is clearly visible

From Fig. 1 it is clear why fatigue resistance of this steel sheet cannot be guaranteed. There must be very high gradient of internal residual stresses and many problems can arise. What is chemical composition good for a mechanical design? Chemical composition and effect of alloying and microalloying are in the interest of the steelworks. Information about chemical composition of used steel is marginal for mechanical design of structures, because it is important only for the welding and it must be guaranteed. On the other hand, in comparison with the problematics of the influence of microstructural changes in heat affected zones of high strength steels is the problematics of chemical composition guarantee negligible for designers and welding engineers. Chemical composition has to be kept under control. Chemical composition of those steels is known very well and can be checked easy. The secret of success in production of those high strength steels consists in combination of chemical composition (microalloying usually), rolling and heat treatment. Final mechanical properties and behaviour of the steel depends strongly on the rolling and heat treatment. How many designers know that form the steel with chemical composition equal to chemical composition of HARDOX 450 can be produced a soft steel with yield point about 350 MPa or real hard HARDOX with yield point about 1400 MPa? The only difference is in the heat treatment. To prove that, let HARDOX 450 undergo normalizing heat treatment and normalized perlitic-feritic microstructure and yield point about 350 - 400 MPa will be the result.

Experimental methods and results

The aim of this paper is to show extended possibilities of mass reduction of the structural elements using the optimizing methods and introducing new steel grades with improved mechanical properties. FEM simulation were carried out using commercial ANSYS software. In this study about 242274 quadratic tetrahedral elements of C3D10 type and 453358 nodes were used in the mesh of analyzed frame (Fig. 2). For optimization of chosen structural element a mesh consisting of 28632 elements and 51573 nodes was used. In preliminary dimensioning of the structural element are achieved maximal tensile stresses, whose values do not exceed 60-100 MPa. This is due to the geometry of the frame and other structural elements, the material properties and the character of the load.

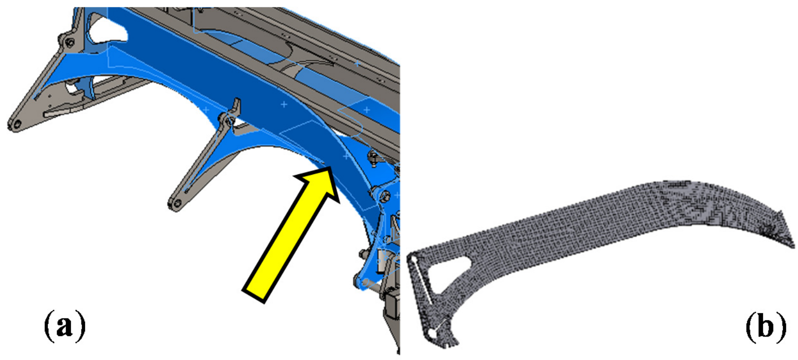

Fig. 2: Example of optimization process; (a) welded frame structure, (b) structural element for optimization

As can be seen from obtained optimization results (Fig. 3a-c) application of modern high strength structural steels can reduce the weight of the structural element from the 140 kg before the optimization to the final weight of 60 kg after optimization, while the relatively high safety coefficient was maintained.

For the comprehensive assessment of the suitability of a change in the thickness of the structural part, the utilization only of optimization calculation is not fully adequate and other experimental tests, such as fatigue tests, are required. This will allow achieve a relevant comprehensive results of the structural part optimizing, which will be able to reliable functionate during their operational lifetime.

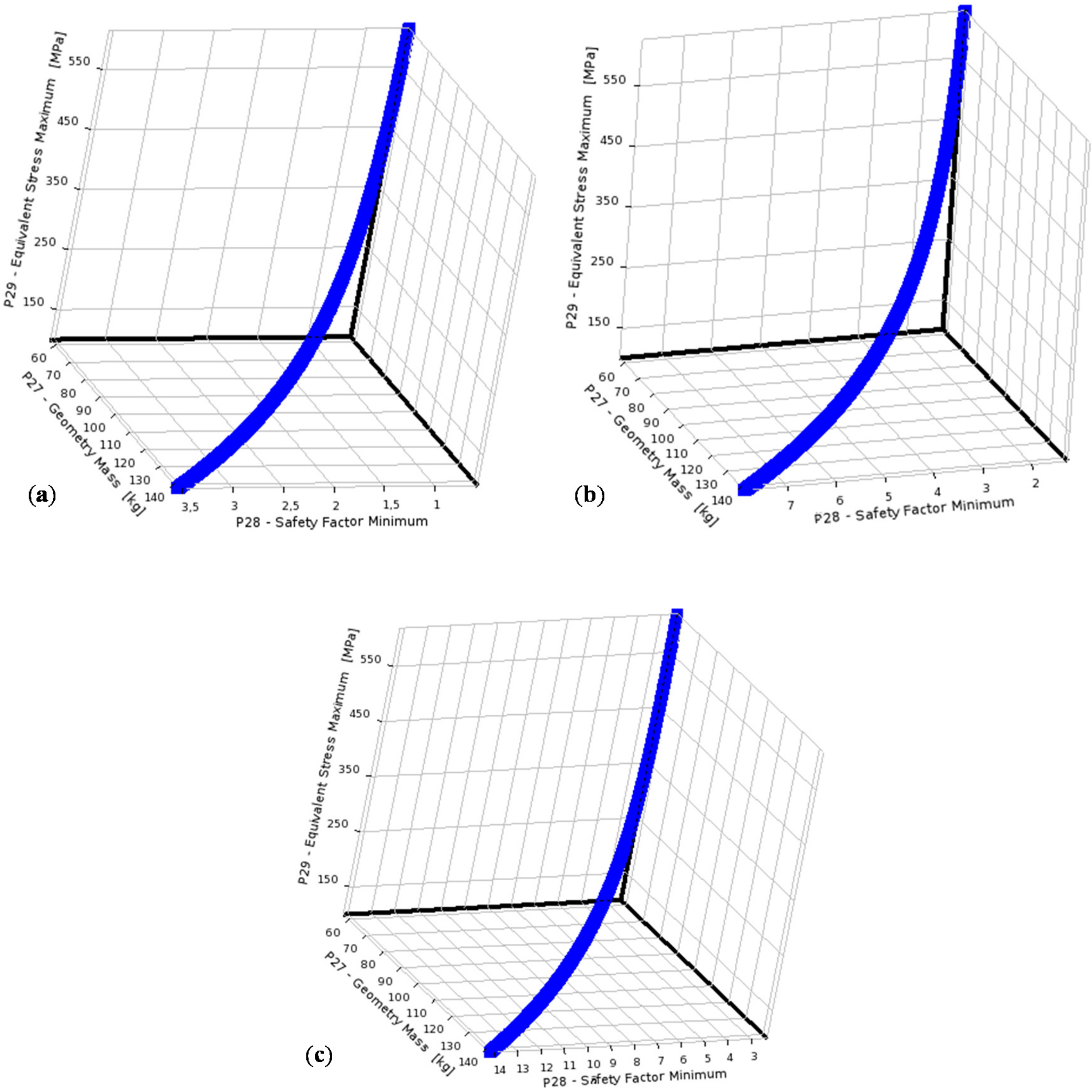

Fig. 3: Example of optimization results for study of stress - safety coefficient - weight of structural part made from: (a) S355 J2, (b) STRENX 700MC, (c) HARDOX 450 steel

Three point bending fatigue tests were carried out at ambient temperature of laboratory air using Amsler 150 HFP 5100 resonant type fatigue testing machine. The fatigue tests with sinusoidal loading were carried out in accordance with the DIN 5010 standard – the S/N curve was determined for assumed stress levels. The experimental set-up illustrating the three point bending loading applied using Zwick/Roel Vibrophore type fatigue testing machine Amsler 150 HFP 5100 can be seen in Fig. 4.

Specimens taken directly from delivered steel sheets were used for the fatigue tests. The rolled plates of S355J2, STRENX 700MC and HARDOX 450 steels with thickness of 10 mm were cut to the required dimensions (15 mm × 55 mm) by water jet abrasive cutting. After that the cutting surfaces were fine grinded to remove possible surface imperfections and influences of cutting process on the material behaviour. Specimens were taken from each steel in the longitudinal orientation to the rolling direction. Finally smooth rectangular (15 × 10 × 55mm) specimens without notches were loaded by sinusoidal cyclic bending using the testing frequency of 100 Hz. Some broken specimens from the fatigue tests of STRENX 700MC and HARDOX 450 steels are documented in Figs. 5 and 6.

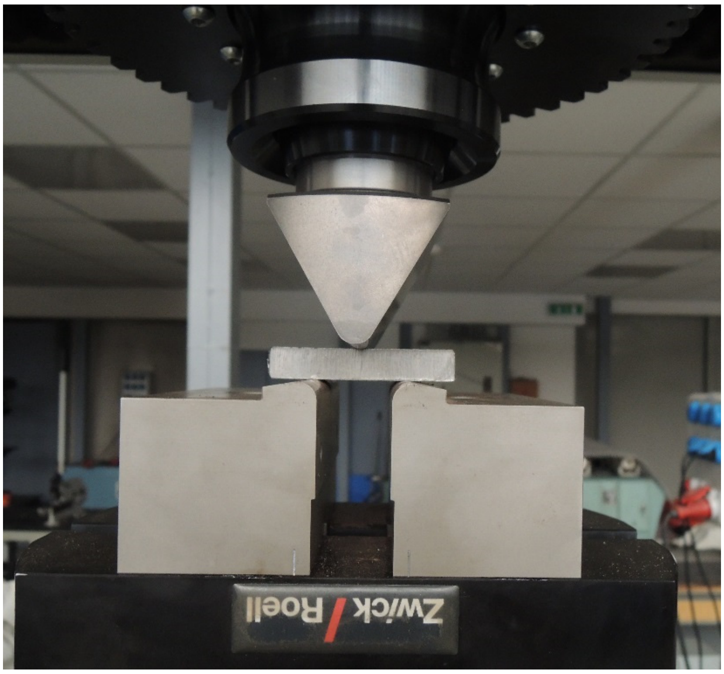

Fig. 4: The Amsler 150 HFP 5100 – resonant fatigue testing machine with equipment for three-point bending fatigue tests

Fig. 5: Example of STRENX 700MC broken specimens after three-point bending fatigue tests

Fig. 6: Example of HARDOX 450 broken specimens after three-point bending fatigue tests

Obtained results of three-point bending fatigue tests of S355J2, STRENX 700MC and HARDOX 450 steels are shown in Fig. 7.

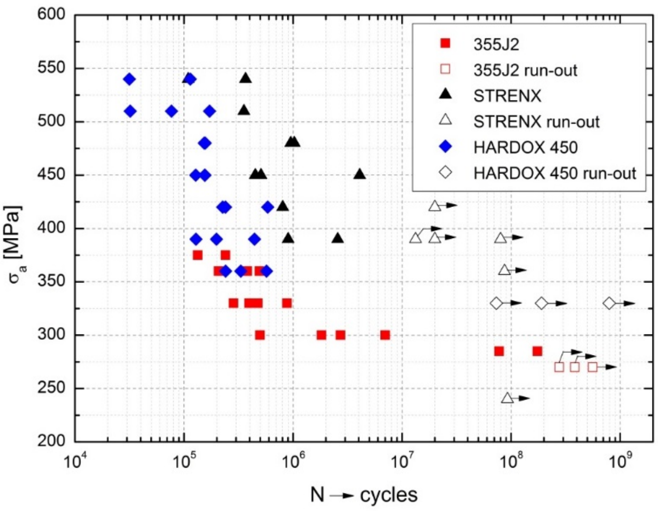

Fig. 7: The fatigue endurance of S355J2, STRENX 700MC and HARDOX 450 steels; the three-point bending fatigue test.

Conclusions

Modern design of the lightweight steel structures using the FEM optimizing methods and introducing new steel grades with improved mechanical properties connected with their fatigue testing used in this study shows extended possibilities of mass reduction and minimization of the risk potentiality of unexpected failures of modern lightweight structures.

Numerous studies have observed that the fatigue endurance of structural steels increases with increasing yield strength and ultimate tensile strength. In this study was found that the increase of tensile strength (see Tab. 2) is not in all cases accompanied by corresponding increase of fatigue properties (see Fig. 7). Some factors influencing this phenomenon were studied and obtained results of microstructural and fractographic analysis gave relevant information about real fatigue behaviour of tested steels. Results obtained from optimization process (Figs. 2, 3) and fatigue tests (Fig. 7) finally resulted in successful and safety design of real lightweight structure. The only way how to reduce the risk potentiality of unexpected failure of modern lightweight structures manufactured from high strength structural steels is to include the knowledge of their fatigue behaviour in to mechanical design and manufacturing processes.

Acknowledgement

This work is partially supported by the Ministry of Education, Youth and Sports of the Czech Republic and the European Union (European Structural and Investment Funds - Operational Programme Research, Development and Education) in the frames of the project "Modular platform for autonomous chassis of specialized electric vehicles for freight and equipment transportation", Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293.

References

[1] M. Petrů, T. Martinec, J. Mlýnek, Numerical model description of fibres winding process for new technology of winding fibres on the frames, Manufacturing Technology. 16 (2016) 778–785.

[2] H. Eschenauer, N. Olhoff, W. Schnell, Applied Structural Mechanics, Fundamentals of Elasticity, Load-Bearing Structures, Structural Optimization, Springer 1997, pp. 301-306.

[3] R. Ulewicz, F. Nový, Fatigue life of high strength steel for cold forming, Metalurgija, 56 (2017) 115-118.