Intelligent Advisory System for Supporting Redesign

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ABSTRACT

It is the designer's dream to be guided by decisions based on physical and mathematical modeling simulations, which are computationally intensive but offer immense insight into developing product. Nevertheless, dealing with these kinds of multi-disciplinary analyses is still a tremendous challenge. The main purpose of the intelligent consultative system for supporting analysis-based redesign, which is presented in this paper, is to engage with this challenge. The results of engineering analysis are often basic parameters for the optimization process. If the structure does not satisfy given criteria, certain optimization steps, such as redesign, have to be performed. Yet, the existing software still fails to provide any advice about these redesign steps. Thus, the selection of the appropriate redesign actions still depends mostly on the designer's knowledge and experience. The idea for our research work was to collect, organize, and write this kind of knowledge and experience into a knowledge base of the intelligent system. The results of the expert evaluation of the system and some tests with real-life examples show that the prototype of the presented intelligent system can be applied either to design new products in practice or as an educational tool.

Keywords: structural analyses, decision support, knowledge-based systems, Prolog

1. INTRODUCTION

Nowadays, designers work under the strong pressure of high technology. The market demands new high quality products in the shortest possible time. They are forced to use all modern methods and tools in order to be successful. In this respect, design and computing are inseparably linked in the modern development process of new products. Computer Aided Design (CAD) applications cover different design stages, like modeling, kinematics simulations, structure analysis or just drawing technical documentation, but they fail to provide help in more creative parts of design process that involve complex reasoning, as for example when possible design solutions need to be evaluated. This is often the reason for completely wrong conclusions, especially because young generations of engineers tend not to understand basic theory or their knowledge and experiences are very limited.

In order to overcome this bottleneck we believe the "intelligent behavior" should be added to the present CAD systems. Designer with lack of experience needs advice to be able to make the right decisions within design process and consequently to design optimal structures.

The idea is to apply intelligent advisory computer system that will be able to provide that kind of support to design process.

In this paper a prototype of the intelligent advisory system for supporting redesign (Fig. 1) is presented. It was not our intention to develop a completely new "intelligent CAD" system, but to provide designer with additional tool that can help him or her in decision making process and at the same time to make the best of the existing CAD software.

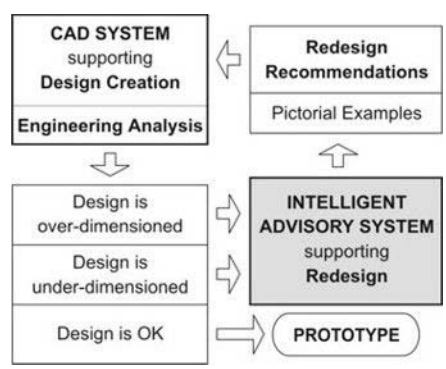


Fig. 1. Intelligent redesign system.

2. ANALYSIS-BASED DESIGN OPTIMIZATION

Optimal design performed at the first attempt is rare in engineering. Design is an iterative process. How many iterations/cycles are needed directly depends on the quality of the initial design and appropriateness of the later redesign actions.

The purpose of engineering analysis (using for example Finite Element Method - FEM) [1] in design process is to simulate and verify the conditions in the structure, as they will appear during its exploitation. If the structure does not satisfy given criteria, it needs to be improved by applying certain optimization steps, such as redesign, use of other material, etc. A decision about what should be done directly depends on the correct interpretation of the results of the analysis. A lot of knowledge and experience is needed to be able to understand the results of the analysis and to choose the appropriate optimization measures. In spite of rapid progress in the field of graphics, workstations and corresponding software, the existing computer tools for post-processing the results of the engineering analyses still allow completely wrong conclusions, and fail to provide advice about further optimization steps. The easiest design change is a selection of a different material. Yet, it is not always an option and in many cases, it is financially unjustified. Fig. 2 presents a simple example of initial design with some redesign possibilities in case the structure is over- or under-dimensioned.

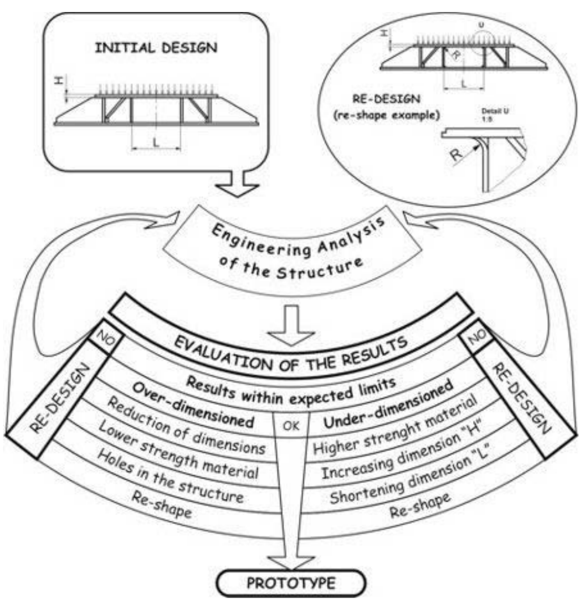


Fig. 2. Example of redesign possibilities.

The list of possible redesign actions is case-by-case solution of quite complicated problem that requires knowledge about the principles of mechanics, structures and materials technology. The experiences gained with many redesign iterations are of crucial importance. As a rule, there are several redesign steps possible for design improvement. The selection of one or more redesign steps that should be performed in a certain case depends on the requirements, possibilities and also on wishes.

The analysis-based design optimization is certainly one of the engineering tasks with a great potential for intelligent systems application. For example, in ship design such a system is reported as a useful tool to reduce the burden of the designer in selecting a proper design after numerical optimization [2]. There are many other research activities in the field of applying artificial intelligence to analysis-based design optimization [3-6]. In this context, our idea was to encode the knowledge and experience to create the rules for proposing correct redesign actions and to develop an intelligent advisory system for redesign recommendations.

3. SYSTEM DEVELOPMENT

Development of the proposed intelligent redesign system has been carried out in some consecutive steps. Knowledge acquisition and development of the knowledge base were the first and the most important ones. The theoretical and practical knowledge about design and redesign actions were investigated and collected. After that, the appropriate representation formalism for the acquired knowledge was defined and the knowledge base of the system was encoded. Finally, we developed the shell of the system named PROPOSE consisting of the user interface and inference engine suited to the existent knowledge base. The knowledge base and the shell of the system are encoded in Prolog [7] syntax. Visual Prolog version 5.2 [8] was used for that purpose.

Redesign involves a great amount of different knowledge. The literature, where this knowledge and experience are collected and documented is very scarce. On the other hand, the extensive knowledge and experience is concentrated at not so many human experts, who work on design problems for many years.

We decided to take all possible ways to acquire redesign knowledge, from literature survey and examinations of the old engineering analyses to the interviews of some human experts. It was not an easy task. For example, many reports about the analyses contain some confidential data and are not allowed to be used. On the other hand, interviews and examination of the existing redesign elaborates are conditioned by cooperation with several experts and can be time-consuming. Therefore, the scope of results is very much limited by the experts. However, we should realize that even experts at the same field have quite different opinions and they also admit many exceptions to their own rules!

According to the results of basic research, the production rules were selected as the appropriate formalism for encoding knowledge. Each rule presents a list of recommended redesign actions that should be taken into consideration, while dealing with a certain problem limited with some limits. The rules are generalized and do not refer only to the examples that were used during the knowledge acquisition process. They can be used every time when the problem and limits match with those in the head of the rule. In such a case, the application of the appropriate rule would result in the list of recommended redesign actions for dealing with the given problem. Some pictorial examples were added to the system for additional help to the user to better understand the proposed redesign actions and to make an adequate chose.

4. THE KNOWLEDGE BASE

From the technical point of view, the most important rules in the knowledge base are those defining case-driven redesign recommendations. However, there are many other rules that are also necessary for the system to be functional. Thus, the knowledge base contains the following types of the rules:

- rules defining redesign recommendations,
- rules proposing general design changes,
- rules determining the "size" of the problem,
- rules defining the status of the structure,
- rules explaining proposed changes by using the text or the picture,
- rules supporting the evaluation of the analysis results' reliability, and
- rules checking the justification for redesign.

In addition to the production rules, a part of the knowledge is written in the knowledge base in form of the facts, as follows:

- facts about material properties (Young modulus and expansion coefficient),
- facts containing different comments for the user, and
- facts enabling the explanation of the proposed changes.

Let us present an example of the rule that define redesign recommendations for a certain design case. Fig. 3(a) presents a design problem of high temperatures appearing in a small area between the valve seats on the gas side of the fire deck being part of the internal combustion engine. These kinds of problems are quite frequent in design practice and can be solved by applying several different design changes. The introduction of an air gap that redirects the heat current is proposed as a design solution in Fig. 3(b).

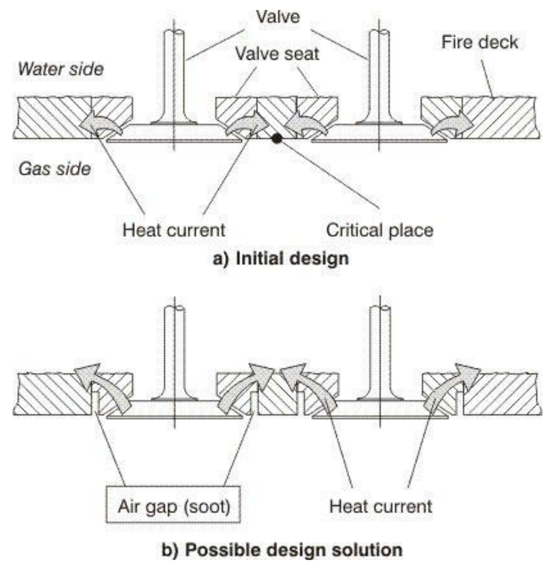


Fig. 3. Design problem – local area with high temperature.

Considering some other redesign recommendations for this case, the following redesign rule was defined:

IF temperature is too high
AND area is small and narrow
THEN
Use higher thermal conductible material
Use material with higher strength at high temperature
Add material – make wider area or add vertical cooling rib
Move the heat contact area – redirect the heat current

In the knowledge base the extended rule is encoded in Prolog syntax as follows:

```
actions(
["use higher termal conductible material",
 "use material with higher strength at high
  temperature"],
["decrease the heating area",
 "increase cooling area, (e.g. add cooling rib)",
 "reduce the distance between the source of the
  heat and cooling media"],
["ensure more efficient cooling: lower temperature
  of the media",
 "or ensure more efficient cooling: heigher
current
  velocity",
 "move the heat contact area out of the critical
  region (e.g. with a gap)",
 "redirect the heat current",
 "choose another cooling media"],
["temperatures are high"]) :-
            temperatures(high),
            area_description(one,short_narrow).
```

5. THE SHELL OF THE SYSTEM

The shell of the system was encoded in Prolog. Prolog was chosen because of its built-in features rule-based programming, pattern matching and backtracking, which are excellent tools for developing an intelligent system. Our work was concentrated on declarative presentation of the knowledge, as we used the data–driven reasoning, which is again built in Prolog. However, some control procedures were also added to the inference engine of the system to adjust the sequence of the redesign steps to the real-life design process. Much more effort was put into development of the user interface to enable the appropriate communication between the user and the system.

The user interface enables the user to input the data, informs the user about the results, offers help and presents the information about the inference process. At any time the list of possible choices (between the square brackets, []), and a default selection (between the signs for smaller and greater, <>), are presented to the user.

The shell of the system consists of 255 rules and 80 facts. The total number of the procedures is 142, where 7 of them are for the inference engine and 115 for the user interface. The additional 20 subsidiary procedures are used for the proper communication with the operating system and enable the use of picture viewer to present the pictorial examples.

For the time being, the system is still in development phase and is written as the console application. As such, it is more convenient for testing and frequent immediate changes. In the future, the executive version of the system with graphical user interface is also planed to be made.

6. APPLICATION OF THE SYSTEM

In order to use the system the user simply needs to run the executive version of the system with filename "PROPOSE.exe". The execution starts with the system introduction presented on the screen including some basic information how to use the system. From that point the system leads the user from the specification of the problem to the final conclusions.

First, the user needs to present the information about the results of the engineering analysis. The results have to be both, available and reliable. If the results for the structure to be optimized do not exist, the user is advised to perform the engineering analysis and the system terminates. On the other hand, the user may have the results of the engineering analysis, but the reliability of these results is questionable. In this case the system offers help to the user to clarify whether the results of the engineering analysis are reliable and can serve as basic parameters for design optimization. This part of the dialogue is avoided if the user positively answers the first question, which means that the results are available and reliable.

The type of the engineering analysis needs to be specified in the next step. The current version of the system can deal with the results of strain-stress or thermal analysis. Thus, the user can select just one of these two types. The system selects that the results represent strain-stress analysis if the user do not select any of the available type. The user is informed about that "automatic" selection.

The results of the engineering analysis need to be compared with the allowable limits for the stresses and deformations or, in case of thermal analysis, also for the temperatures. Currently, it is anticipated that the user knows these limits, which depend on the material as well as on the type and the purpose of the structure being analyzed. In the future, the allowable limits could be included into the knowledge base.

The user is asked to present the results of engineering analysis by giving the information for how many percents the maximum computed values are greater or smaller that the allowable limits. According to this user input, the status of the structure (under-dimensioned, over-dimensioned or almost ideal) and the "size" of the changes needed to optimize the structure (significant, minor or none) are defined.

The next step is to clarify redesign justification. In case the maximum computed values are smaller than the allowable limits for less than 10%, the structure is "almost ideal" and changes are not needed at all. If the structure is not stiff enough or it is under-dimensioned, changes are necessary and the system itself classifies them as justified. However, if the structure is over-dimensioned and the maximum computed values are smaller than the allowable limits for more than 10%, significant changes are needed to optimize the structure, yet the user has to decide whether design changes are justified or not. In this case, the system warns the user that design optimization is justified in mass production and can reduce product costs as well as the weight of the product.

When design changes are necessary or justified, the system application proceeds with the selection of the type of the structure. For the time being, the knowledge base includes the rules for the beams and for the general three-dimensional structures. The next step is abstract description of the problem area, where the stresses, deformations or temperatures are the largest. This description has to be made by using the predefined attributes, as for example "uniform area around the hole" or "in corner" or "notch area" (Fig. 4).

In case the problem area can be described in different ways, it is advisable to do so, as the system will be able to propose more possible improvements.

For every problem area, the system searches for the redesign recommendations in the knowledge base. The results are written on the screen as it is presented in Fig. 5. As it was mentioned before, the user can also get the insight into the inference process. If the user requires, the system presents all the steps that led to the final conclusion together with the redesign recommendations. The example of inference process explanation can be seen in Fig. 12, in the next section.

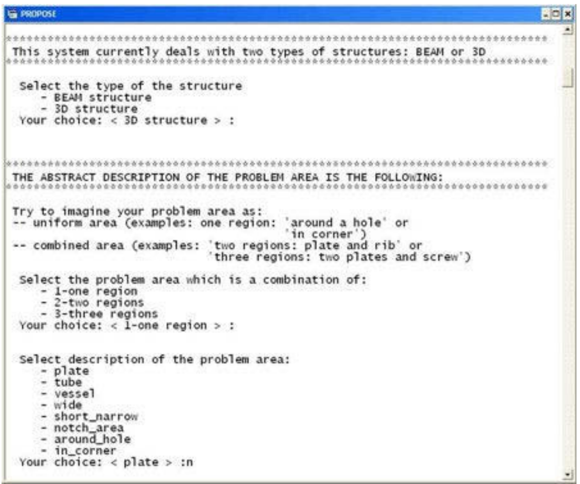


Fig. 4. Description of the problem area.

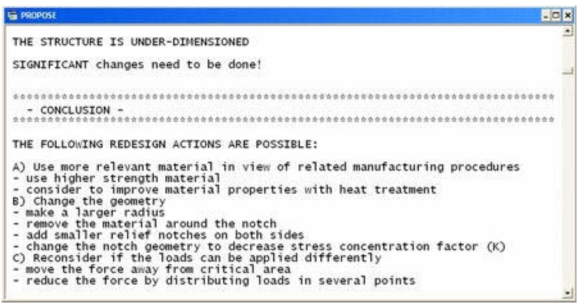


Fig. 5. Results – redesign recommendations.

In addition to the explanation of the inference process, the user can also get more information about certain redesign proposals. This kind of information is provided not only for the geometry changes, but also to support the selection of more relevant material. Redesign proposals are explained with text or with pictorial examples. Some proposals are explained in either ways (Fig. 6 and Fig.7).

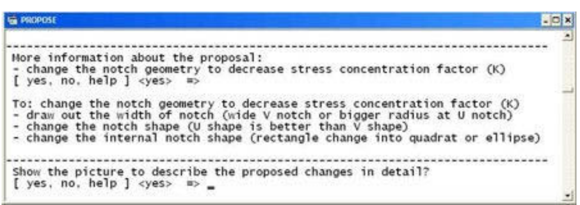


Fig. 6. Text explanation for the redesign proposal.

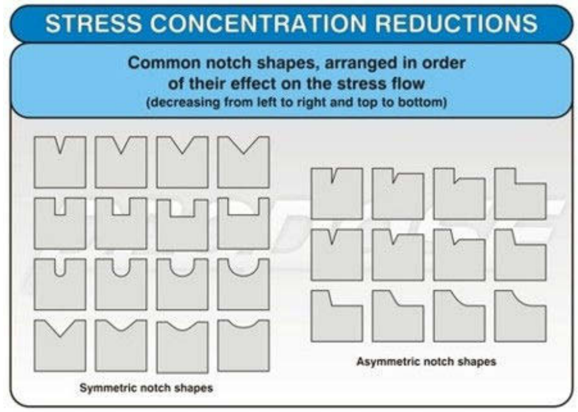


Fig. 7. Pictorial explanation for the redesign proposal.

At the end of every application the user is asked to specify the name of the output file where the results are saved. The filename "Propose.rez" is proposed by the system, yet to build a record about the whole optimization process different filenames should be used for every consecutive application of the system. The output file contains the same information as the explanation of the inference process.

7. EVALUATION OF THE SYSTEM

The evaluation of the system was performed in two ways:

- The experts, who were already involved in the knowledge acquisition process, evaluated the system, when it was ready for use.
- Some real-life examples were used to test the performance of the system.

All comments and suggestions, presented by the experts that were performing the expert evaluation of the system, were taken into consideration and resulted into numerous corrections and adjustments of the system.

One of the testing examples was a shaft of a motorbike engine that was originally modeled by the students. For the initial design two FEM analyses were performed, one for the aluminum shaft (Fig. 8) and the other for the shaft made of iron grey cast.

The results of the FEM analyses have predicted gradients of the stresses in the ear of the shaft, and at the connection of the rod and the ear respectively. In both cases, the computed values were greater than the allowable limits. Similarly, the displacements in the ear of the shaft also exceeded the allowable value. Considering the results of the initial FEM analysis the redesign was certainly needed. Since the maximal stresses for the aluminum shaft were more than three times greater than the allowable limit, it was obvious that aluminum is not strong enough to be used for the shaft loaded as it was considered in the analysis. Thus, we decided to optimize only the shaft made of iron grey cast.

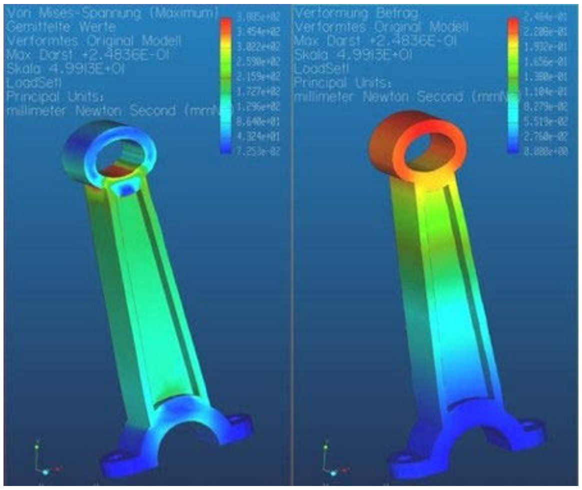
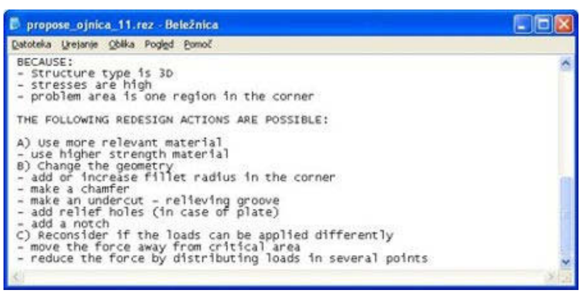


Fig. 8. The results of the initial analysis.

The results of the analysis were presented to the system PROPOSE. The computed displacements were greater than the allowable limit for more than 10%, while relative difference between the computed and allowable stresses was a little smaller than 10%. Since the greatest stresses occurred in the corner where the ear of the shaft is connected to the rod, the problem area was described as "one region in the corner". The redesign actions, proposed by the system PROPOSE for this problem area, are presented in Fig. 9.


propose_ojnica_11.rez - Beležnica

Datoteka Urejanje Oblika Pogled Pomoč

```
BECAUSE:
- Structure type is 3D
- stresses are high
- problem area is one region in the corner

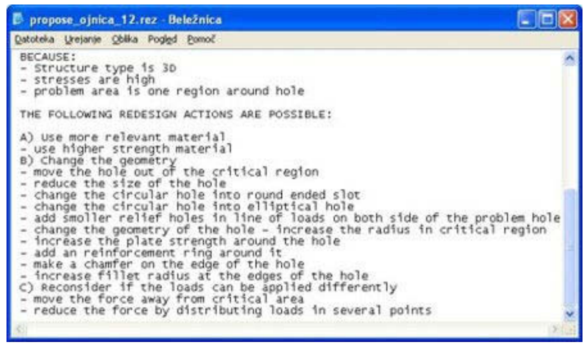
THE FOLLOWING REDESIGN ACTIONS ARE POSSIBLE:

A) Use more relevant material
- use higher strength material
B) Change the geometry
- add or increase fillet radius in the corner
- make a chamfer
- make an undercut - relieving groove
- add relief holes (in case of plate)
- add a notch
C) Reconsider if the loads can be applied differently
- move the force away from critical area
- reduce the force by distributing loads in several points
```

Fig. 9. Redesign proposals ("in corner").

The first redesign recommendation, proposing the use of more relevant material was already carried into effect, as we chose the material with higher allowable stresses. The difference between the computed and allowable limits was reduced significantly, yet the shaft was still under-dimensioned. Thus, the change of the material itself just alleviated the problem that still has not been solved adequately. From the proposed geometry changes we chose the one proposing to add or increase fillet radius in the corner. Fillet radius was added at the connection edges between the ear and the rod of the shaft.

The second area with high stresses at the shaft was in the middle lower point of the ear. According to our judgment, fillet radius at the connection of the ear and the rod would not reduce the stresses in that particular area. Therefore, we applied system PROPOSE again. This time the problem area was described as "around hole", and the system proposed another list of possible redesign actions (Fig. 10). However, all proposals were not applicable. For example we could not change the shape of the hole in the ear from the circle to the ellipse. Instead we choose to apply two other proposals: "reduce the size of the hole" and "add a reinforcement ring around it".


propose_ojnica_12.rez - Beležnica

Datoteka Urejanje Oblika Pogled Pomoč

```
BECAUSE:
- Structure type is 3D
- stresses are high
- problem area is one region around hole

THE FOLLOWING REDESIGN ACTIONS ARE POSSIBLE:

A) Use more relevant material
- use higher strength material
B) Change the geometry
- move the hole out of the critical region
- reduce the size of the hole
- change the circular hole into round ended slot
- change the circular hole into elliptical hole
- add smoller relief holes in line of loads on both side of the problem hole
- change the geometry of the hole - increase the radius in critical region
- increase the plate strength around the hole
- add an reinforcement ring around it
- make a chamfer on the edge of the hole
- increase fillet radius at the edges of the hole
C) Reconsider if the loads can be applied differently
- move the force away from critical area
- reduce the force by distributing loads in several points
```

Fig. 10. Redesign proposals ("around hole").

Considering a dimension of the assembly part, the hole in the ear of the shaft cannot be reduced either. Yet, the proposal to reduce the size of the hole was interpreted slightly different. Instead of reducing the inner diameter, we increased the outer diameter of the ear for 10%. In this way, the same effect was achieved, as if the size of the hole would be reduced at the same outer diameter of the ear. The thickness of the reinforcement ring around the hole was defined as 10% of the ear thickness, while the outer diameter of the ring was set to the middle value between the outer and inner diameter of the ear. Finally, the following changes were made to initial design after the first optimization cycle:

- the fillet radius was added at the connection of the ear and the rod,
- the outer radius of the ear was increased, and
- the reinforcement ring was added at both sides of the hole in the ear.

The new redesigned version of the shaft was analyzed again. This time the stress-strain FEM analysis was performed only for the shaft made of iron grey cast. The results of the analysis (Fig. 11) confirmed that the redesign actions were chosen correctly, as the stresses in problem area were reduced significantly. The only gradient of the stresses that still exceeded the allowable limit remained in very small area at the sharp outer edge of the ear. It was decided to add fillet radius at that edge too.

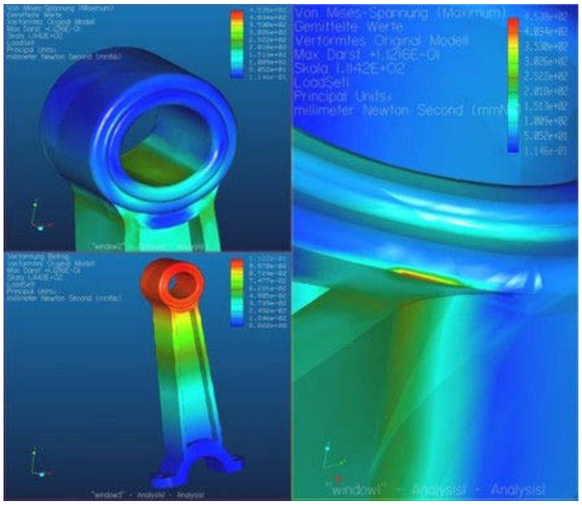
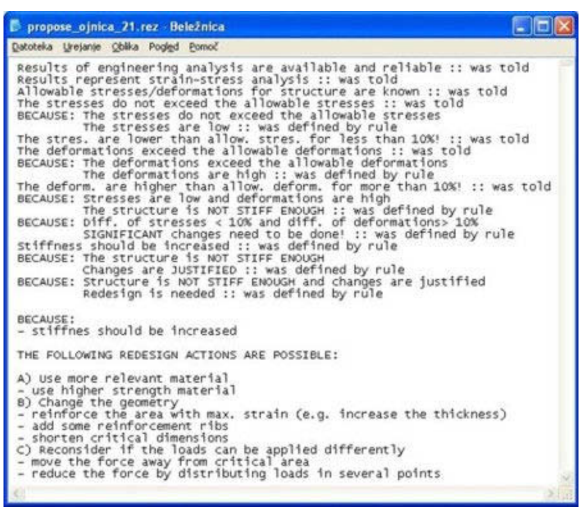


Fig. 11. The results for the second version of the shaft.

The deformations were reduced significantly. However, they were still too high to be satisfied. Thus, we started the next design optimization step to reduce the deformations by applied the system PROPOSE again. This time, only the deformations were presented as greater than the allowable limits for more than 10%. The content of the output file presenting the inference process explanation and the proposed redesign recommendations for the second version of the shaft is shown in Fig. 12.



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propose_ojnica_21.rez - Beležnica
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Results of engineering analysis are available and reliable :: was told
Results represent strain-stress analysis :: was told
Allowable stresses/deformations for structure are known :: was told
The stresses do not exceed the allowable stresses :: was told
BECAUSE: The stresses do not exceed the allowable stresses
         The stresses are low :: was defined by rule
The stres. are lower than allow. stres. for less than 10%! :: was told
The deformations exceed the allowable deformations :: was told
BECAUSE: The deformations exceed the allowable deformations
         The deformations are high :: was defined by rule
The deform. are higher than allow. deform. for more than 10%! :: was told
BECAUSE: Stresses are low and deformations are high
         The structure is NOT STIFF ENOUGH :: was defined by rule
BECAUSE: Diff. of stresses < 10% and diff. of deformations> 10%
         SIGNIFICANT changes need to be done! :: was defined by rule
Stiffness should be increased :: was defined by rule
BECAUSE: The structure is NOT STIFF ENOUGH
         Changes are JUSTIFIED :: was defined by rule
BECAUSE: Structure is NOT STIFF ENOUGH and changes are justified
         Redesign is needed :: was defined by rule

BECAUSE:
- stiffnes should be increased

THE FOLLOWING REDESIGN ACTIONS ARE POSSIBLE:

A) Use more relevant material
- use higher strength material
B) Change the geometry
- reinforce the area with max. strain (e.g. increase the thickness)
- add some reinforcement ribs
- shorten critical dimensions
C) Reconsider if the loads can be applied differently
- move the force away from critical area
- reduce the force by distributing loads in several points
```

Fig. 12. Redesign proposals for the stiffness problem.

After the evaluation of the proposals, it was decided to increase the thickness and to add the reinforcement rib. To reduce the deformations at the area around the ear of the shaft, we made the following redesign changes:

- the fillet radius at connection of the ear and the rod was increased to increase the thickness of the rod at the connection area,
- the outer diameter of the ear was increased a little bit more,
- the outer diameter of the reinforcement ring was set the same as the outer diameter of the ear, and
- the reinforcement rib was added in the middle of the rod just bellow the ear.

The next stress-strain analysis was also the last one, as the results (Fig. 13) proved that we have reached the final design. The maximal deformations were reduced and were less than the allowable limit, while the stresses did not change significantly.

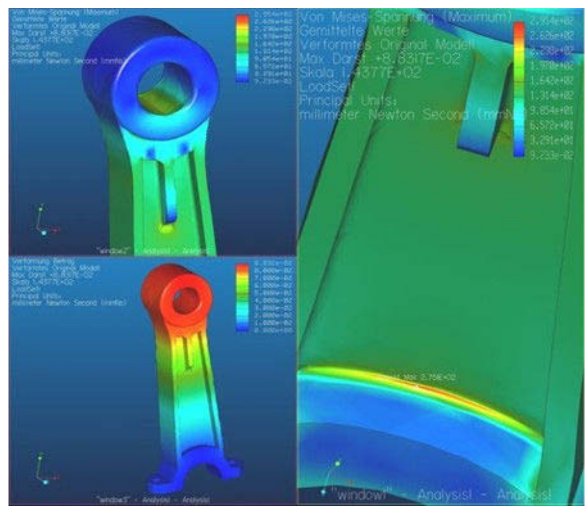

Fig. 13. The final results for the shaft.

8. CONCLUSIONS

Decision for development of the intelligent advisory system for redesign is mostly the result of experiences acquired through the design education process [9]. The aim of our research work was to develop an intelligent system, which would be able to support the user (designer or student) through analysis-based design optimization process, especially at the design verification and redesign phase. This paper presents a prototype of such computer system.

When using the system PROPOSE, a designer has to answer some questions stated by the system to present the results of the engineering analysis with emphasize to the problem area that needs to be optimized. These answers are then compared with the rules in the knowledge base and the most appropriate redesign changes that should be taken into account in certain case are determined and recommended to the user. The system provides constant support to the user's decisions in terms of explanations and advises. At the end, the user can get the explanation how the proposed redesign changes were selected and also some more precise information how to implement a certain redesign proposal including some pictorial examples.

It is anticipated; the presented intelligent system will be used not only for optimizing new products in practice, but also in design education. The students are typical representatives of inexperienced designers. Thus, the use of the presented system could be very useful in design education process. In this case, the important feature of the knowledge-based systems, the ability to explain the inference process, will be specially welcome and could enable the students to acquire some new knowledge. It may help them to learn more about basic principles of design process and to avoid many wrong conclusions and mistakes, which are now quite frequent due to lack of experience. We believe the application of our system in the education process can help to prepare the students for their future engineering profession, when their work will be exposed to the competitive "battle" on the market, where optimal design solutions are more and more indispensable.

9. ACKNOWLEDGEMENTS

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