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Make Harmony Between Technology and Nature, and Your Mind will Fly Free as a Bird
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STRUCTURAL EFFICIENCY

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Abstract: *The present work presents a new concept – structural efficiency. Structural optimization allows us to modify a mechanical structure in order to achieve an optimum. Using optimization, we achieve a better structural response with the same material resources or we use less material resources for the same structural response. Even the structural optimization provides an optimum it does not provide any information regarding a global use of material in its main purpose – load carrying. This can be revealed only by this new explicit concept – structural efficiency.*
Key words: *structural efficiency, optimization, new concept*

1. INTRODUCTION

Presently, there is a special interest in using the material resources in a more efficient way. That is why mathematical optimization and numerical structural calculus were successfully combined into structural optimization (Vanderplaats, 2007). It was developed for design (size and shape) optimization and topological optimization (Constantinescu et al., 1999). Using optimization, we achieve a better structural response using the same material resources or we use less material resources for the same structural response. Even the structural optimization provides an optimum, a structural configuration and a structural response it does not provide any information regarding the use of the material from a global perspective in its main purpose – load carrying. This can be revealed by a new explicit concept – structural efficiency Ξ (CSI).

There were some attempts to study the structural efficiency, but based on other approach (Burgess, 1998).

2. STRUCTURAL EFFICIENCY FACTOR

The structure with all the volume reaching the allowable stress is the ideal structure. The structural efficiency in this case is $\Xi = 100$ %. In real cases this level of efficiency cannot be achieved. It is still very important to quantify the level of material use. This can be done using *the structural efficiency factor* Ξ. It is very convenient to use the finite elementh method as base for structural analysis.

Considering an analysis with equivalent stress on element criteria, the average stress of the entire structure is

$$\sigma_{avg}^{elem} = \frac{\Sigma\left(\sigma_i^{elem} \cdot V_i^{elem}\right)}{\Sigma V_i^{elem}}, \qquad (1)$$

where V_i^{elem} is the volume and σ_i^{elem} is the stress of the element *i*.

The adimensional structural efficiency factor is

$$\Xi^{elem} = \frac{\sigma_{avg}^{elem}}{\sigma_{alowable}} \cdot 100\ [\%]. \qquad (2)$$

It is the ratio between the area covered by stress of elements and the one below the allowable stress – figure 1.

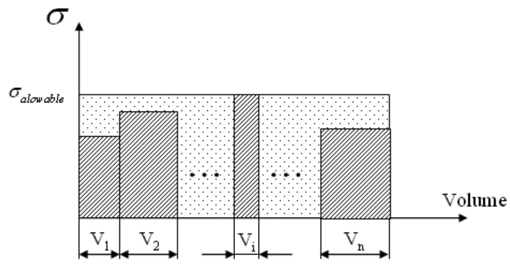

Fig. 1. Structural efficiency for stress on elements criteria

An important mention must be done. The weight of an element stress is given by its volume.

Considering stress on node the evaluation criteria of the structural response, we will calculate the "equivalent volume" of node *i*. This one is in fact the average of the elements volume that contains the node *i* – figure 1.

$$\mathrm{V}_{\mathrm{i}}^{\mathrm{node}} = \frac{\Sigma_j^m V_j^{elem}}{j}, \qquad (3)$$

where V_j^{elem} is the volume of the element *j*. This calculus must be done for all nodes of the structure before going to the next step. This calculus requires the node connectivity of elements.

The average stress of the entire structure is

$$\sigma_{avg}^{node} = \frac{\Sigma\left(\sigma_i^{node} \cdot V_i^{node}\right)}{\Sigma V_i^{node}}, \qquad (4)$$

where V_i^{node} is the "equivalent volume" and σ_i^{node} is the stress of the node *i*.

The adimensional structural efficiency factor is

$$\Xi^{node} = \frac{\sigma_{avg}^{node}}{\sigma_{alowable}} \cdot 100\ [\%]. \qquad (5)$$

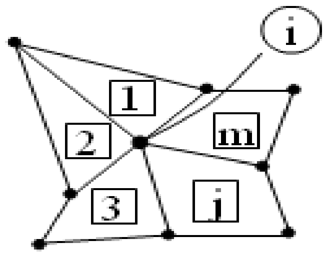

Fig. 2. Node connectivity of elements

3. STRUCTURAL OPTIMIZATION

3.1 Size optimization

We will present a simple, classical example of a structural size optimization. The structure is the arm of an offshore floating crane.

Before optimization the stress on element using von Mises criteria are presented in figure 3.

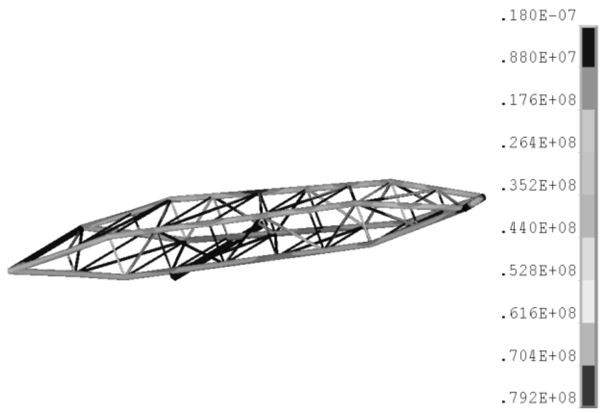

Fig. 3. Stress on elements before optimization

The maximum equivalent stress is 79 MPa. The allowable stress is 150 MPa. We will consider it as a restriction and we will perform the optimization.

We will consider as variables the dimensions of the cross sections of trusses. The objective function is the mass. Minimizing it by achieving the convergence of the solution into the imposed tolerance we obtain the results presented in figure 4.

Even if we obtained the optimum structure from a practical approach it is not an ideal one from a theoretical point of view. This will be quantified by the structural efficiency factor.

3.2 Structural efficiency calculus

The efficiency of the material use will be calculated using the above mentioned Ξ factor.

A programme in two variants was developed in order to perform the required tasks.

One variant was developed for equivalent stress on element criteria and the other for equivalent stress on node criteria.

The first variant is a very fast one requiring a small amount of calculus.

The resulting structural efficiency factor is $\Xi^{elem} = 62$ [%].

Even von Mises equivalent stress on element is a criteria validated by experiments it is not so used as usual as von Mises equivalent stress on node criteria.

The second variant uses von Mises equivalent stress on node. It requires an increased amount of calculus because it must check the node connectivity of all elements. This part of software code is susceptible for important improvements, depending on the chosen algorithm.

The resulting structural efficiency factor in this second approach is $\Xi^{node} = 61$ [%].

Another configuration with different values of design variables can lead to a non optimum structure from an optimization classical point of view – figure 5.

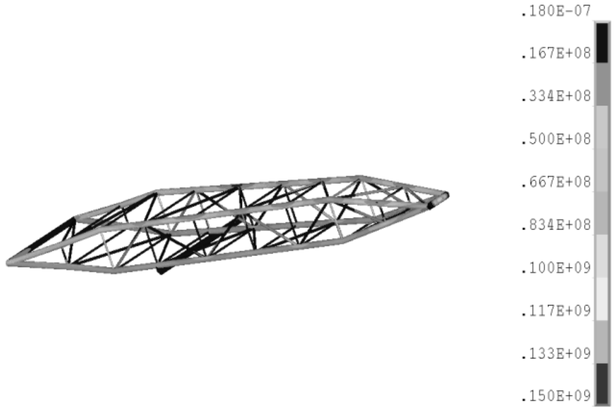

Fig. 4. Stress on elements after optimization

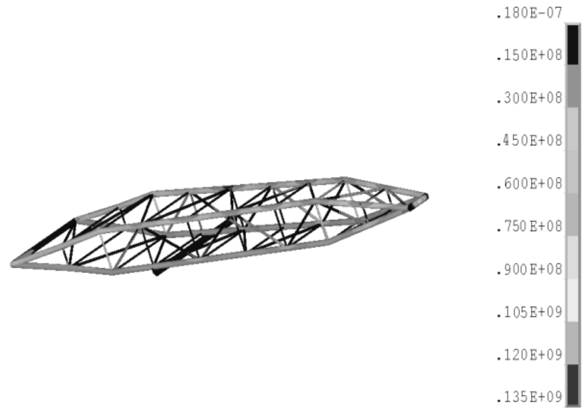

Fig. 5. Stress on an unoptimized structure

But at a closer look we observe that the structural efficiency factor is $\Xi^{elem} = 68$ [%], even the maximum stress value is 90% (135 MPa) from allowable stress (150 MPa). This reveals that reaching a structural optimum does not offer a global view over using the material into a mechanical structure (Bandrabur et al., 2008), (Hadar & Gheorghiu, 2005).

The optimum structure from defying the problem to the final solution is a technical problem depending on user's ability. The final result can be unbiased quantified only by the structural efficiency factor.

4. CONCLUSIONS

Reaching a structural optimum from a size optimization point of view does not offer all necessary information about using the material into a mechanical structure.

The structural efficiency factor is a very important tool used to quantify the use of material for strength reasons. It was never presented explicit before as in present work.

The difference between structural efficiency factors calculated considering stress on node and stress on element are not significant.

Future research can implement the structural efficiency factor directly into the core of the finite element programs.

Another direction of future study is developing a programme which will be able to calculate the structural efficiency factor considering multiple load cases.

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