Hybrid methodologies of 3D beams reverse geometry analysis with embedded quality tools within the boundaries of a modern computer-aided design system

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ABSTRACT: Modern CAD systems are essential in all phases of designing, evaluating and manufacturing mechanical parts. Efficient integration of CAE tools into modern CAD environments results in highly accurate procedures within a short time frame. In this work, a comparative study is presented, based on two novel hybrid methodologies for evaluating and optimising the reconstruction procedure for a 3D beam with an arbitrary cross-section. Both methodologies combine adaptive meshing techniques with quality tools (Taguchi method and response surface methodology), within the boundaries of a modern CAD system for the formation of the boundary element method (BEM) mathematical model. The application of such a methodology as an integrated CAD/CAE tool offers students and inexperienced engineers an excellent overview on the behaviour of structures in various loading and boundary conditions.

Keywords: CAD systems, hybrid methodologies, adaptive meshing techniques, boundary element method, behaviour of structures

INTRODUCTION

This work further develops previous work by Sagias et al on embedding quality tools in reverse geometry analysis of 3D beams to obtain the model needed for the stress analysis automatically [1]. In the previous work, an adaptive slicing methodology was presented in order to determine the optimum distance between two consecutive cross sections of a beam, on parallel planes, throughout the total length of the beam. This methodology was based on error indicator criteria [2] and quality tools [1] for calculating the equivalent stress on every node of the mesh for every section of the analysed beam; thus, calculating the optimum distance between all sections. The main goal in this work is the usage of surface response methodology (RSM) and the Taguchi approach and providing a comparison in the developed methodology [1][2]. Thus, a comparative study is presented to discern the differences between different embedded tools, applied in hybrid methodology of 3D beams reverse geometry analysis [1][2].

METHODOLOGY

The methodology, as presented in previous work [2], introduced the use of quality tools in a slicing procedure [1] of any arbitrary 3D beam, along its centroidal-axis. It was also generated by exploiting tools and technologies from the application programming interface (API) of any modern CAD solid modeller system. Via this process, the BEM mathematical model is produced automatically, based on the geometrical CAD model, resulting in reduced idealisation errors [3]. As a reference point for this work and applying the methodology, a comparison between the Taguchi approach and response surface methodology (RSM) is presented for adapting the distance between every two consecutive sections on a 3D beam. The quality tools selected for comparison are the Taguchi approach and the response surface methodology. They were built around adaptive methodologies by using the posteriori error indicator [4]. The steps that followed in order to apply the design of experiment (DOE) on both methods are outlined in work by Montgomery [5] and Oehlert [6]:

- Process objective determination;
- Parameters definition affecting the process;
- Appropriate DOE method selection;
- Conduction of experiments;
- Data analysis;

- Evaluation of analysed data.

Following this strategy, the factors and their levels were determined. The two factors are the initial distance between the slices and the tolerance on calculating the final acceptable distance, as used in previous works [1][2]. The results of the error indicator (Equation 1) will be used in both approaches, by using the maximum equivalent stress of each section (σ_{vm}) and determine an upper limit $\overline{\tau_G}$, as set by previous works [10][11].

$$\tau_{\varphi_{k+1}} = \frac{\sigma_{vm}^{k+1} - \sigma_{vm}^{k}}{\sigma_{vm}^{k}} \cdot 100 \leq \overline{\tau_G} \quad (1)$$

Both approaches use the same factors due to the comparison and analysis of all results. For the Taguchi approach, the factors and levels are presented in Table 1. The analysis *signal-to-noise* (SN) ratio *nominal-is-best* (Equation 2) [7-9] was selected, in order to obtain values close to the selected upper limit each time. For the RSM approach, the factors are presented in Table 2.

$$SN_T = 10 \cdot log\left(\frac{\bar{y}^2}{s^2}\right) \quad (2)$$

Table 1: Factors with levels - Taguchi approach.

Factor	Level 1	Level 2	Level 3
Initial distance between slices	5 mm	10 mm	15 mm
Tolerance	0.125%	0.25%	0.5%

Table 2: Factors with levels - RSM approach.

Factor	Lower level	Upper level
Initial distance between slices	5 mm	15 mm
Tolerance	0.125%	0.5%

IMPLEMENTATION

The necessary experiments suitable for the selected factors and levels are presented in Table 3 for the Taguchi approach and Table 4 for the RSM.

Table 3: Experiments - Taguchi approach.

L9 - orthogonal array		
SN of experiment	Factor 1 (mm)	Factor 2 (%)
1	5	0.125
2	5	0.25
3	5	0.5
4	10	0.125
5	10	0.25
6	10	0.5
7	15	0.125
8	15	0.25
9	15	0.5

Table 4: Experiments - RSM approach.

SN of Experiment	Factor 1 (mm)	Factor 2 (%)
1	5	0.125
2	15	0.125
3	5	0.5
4	15	0.5
5	5	0.3125
6	15	0.3125
7	10	0.125
8	10	0.5
9	10	0.3125
10	10	0.3125

11	10	0.3125
12	10	0.3125
13	10	0.3125

This $\overline{\tau_G}$ upper limit, as referred by Charafi [10] is set at 3% or 5%. In the methodology presented here, one more value was used, 7%, which aimed to produce a better perspective in the final results.

IMPLEMENTATION TESTS

The selected part is the same as previous work [2]: an extruded orthogonal section part with 20 degrees taper (Figure 2 and Figure 3).

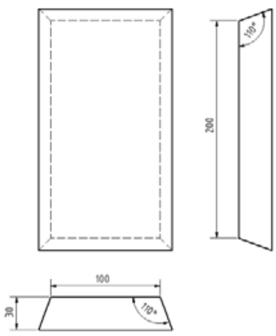

Figure 1: Part used in case study - dimensions.

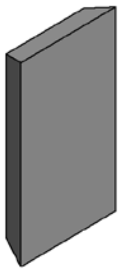

Figure 2: Part used in case study - 3D view.

For the Taguchi approach, the results can be seen in Table 5 and Figures 3 to 5.

Table 5: Results - Taguchi approach.

Level	$\overline{\tau_G}$ = 3%		$\overline{\tau_G}$ = 5%		$\overline{\tau_G}$ = 7%	
	Initial distance between slices	Tolerance	Initial distance between slices	Tolerance	Initial distance between slices	Tolerance
1	2.974	2.974	4.796	4.639	6.434	6.434
2	2.974	2.919	4.640	4.640	6.434	6.434
3	2.861	2.919	4.640	4.796	6.434	6.434
Delta	0.111	0.055	0.156	0.157	0.000	0.001
Rank	1	2	2	1	2	1

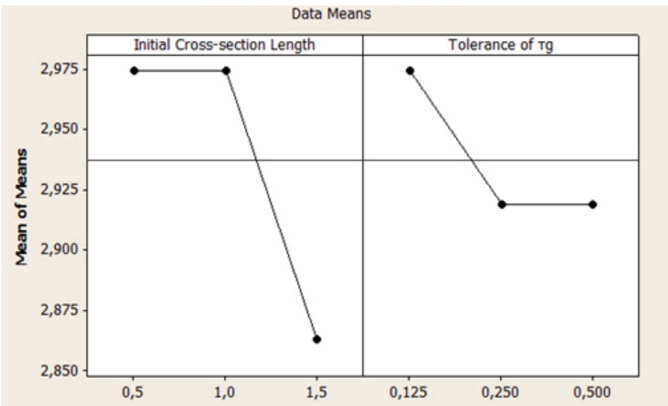

Figure 3: Means plot - $\overline{\tau_G}$ = 3%.

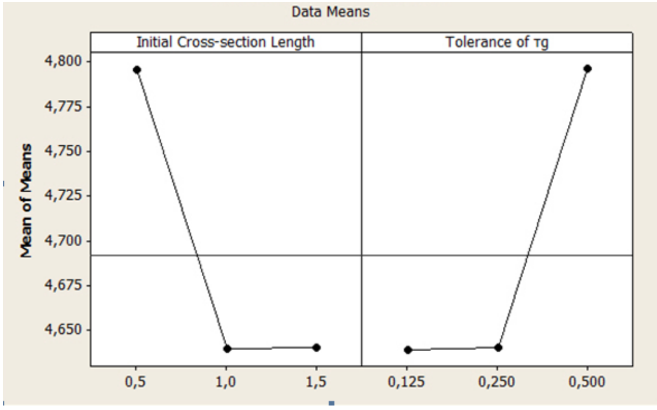

Figure 4: Means plot - $\overline{\tau_G}$ = 5%.

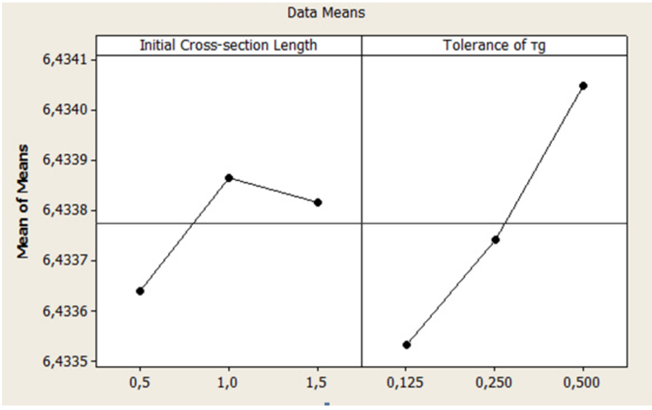

Figure 5: Means plot - $\overline{\tau_G}$ = 7%.

For the RSM approach, the results can be seen in Table 6 and Figures 6 to 8.

Table 6: Results - RSM approach.

$\overline{\tau_G}$ = 3%			$\overline{\tau_G}$ = 5%			$\overline{\tau_G}$ = 7%		
Initial distance between slices	Tolerance	R2	Initial distance between slices	Tolerance	R2	Initial distance between slices	Tolerance	R2
9	0.15	87.69	5	0.5	77.14	15	0.5	83.45

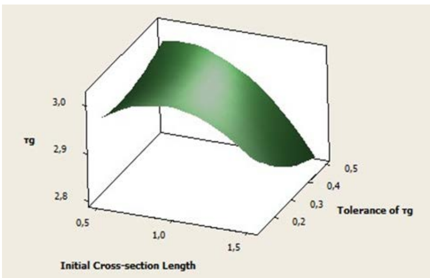

Figure 6: Response surface plot - $\overline{\tau_G}$ = 3%.

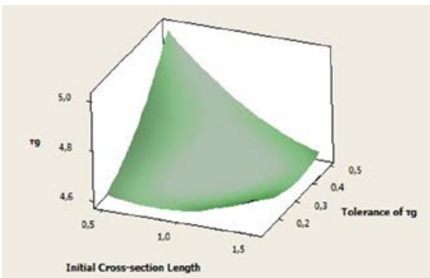

Figure 7: Response surface plot - $\overline{\tau_G}$ = 5%.

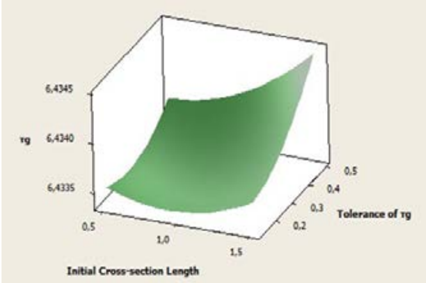

Figure 8: Response surface plot - $\overline{\tau_G}$ = 7%.

Although results on both approaches, Taguchi and RSM, are in the same direction, it is obvious that the selected $\overline{\tau_G}$ value provided different optimum values for the factors. Thus, a generalised motive cannot be generated and it is the main reason for adding the 7% value after conducting the first experiments. When the goal value is set to 3%, then, the Taguchi approach proposes as optimum values 5 or 10 mm of initial distance and the 0.125% tolerance. Also, a weak interaction can be seen between the two factors when the distance and the tolerance have values of 15 mm and 0.125 %, respectively. When applying the RSM, good data fitment were obtained (R^2 = 87.69%) having as optimum values of 8-11 mm for the distance and 0.125-0.17% for the tolerance at the intervals.

It is interesting to observe that when the goal value was set to 5% the results were in the opposite direction. The Taguchi approach proposes a value of 5 mm for the initial distance and 0.5% tolerance as the optimum, with a weak interaction between them. When applying the RSM, good data fitment (R^2 = 77.14%) was not produced; the optimum values were 5 mm for the distance and between 0.44% and 0.5% for the tolerance. Finally, when setting the goal value to 7%, the Taguchi approach proposes as optimum values 10 mm or even 15 mm of initial distance and the 0.5% for tolerance. Here a strong interaction appears between the two factors when the distance and the tolerance have values of 5-10 mm and 0.25-0.50% or even 10-15 mm and 0.125-0.25%, respectively. When applying the RSM good data fitment (R^2 = 83.45%) having as optimum values at 15 mm for the distance and 0.5% for the tolerance were produced.

IMPACT ON ENGINEERING AND TECHNOLOGY EDUCATION

The methodology's implementation and all case studies were conducted in the CAD Laboratory of the Mechanical Engineering Department of the Piraeus University of Applied Sciences, in close collaboration with the Mechanical and Automotive Engineering Department of Kingston University, London. This work's main novelty is the successful implementation of different quality tools in the adaptive slicing procedure to obtain an accurate and quick stress analysis model by correctly reconstructing the CAD geometry. Through the presented methodology, students, professors and engineers of different engineering backgrounds and educational cultures create successful synergies gaining invaluable experience on how to design products by using virtual prototyping tools efficiently.

CONCLUSIONS

A comparative study of embedding different types of quality tools in adaptive slicing procedures has been presented in this work. The objective was to explore the most appropriate methodology to embed in the slicing procedure by using the boundary element method (BEM). The methodology is promising and can be extended to future work by applying it to different types of case study in order to acquire generalised results. Such application of the hybrid methodology with both quality tools will give a generalised view of the results based on the type of case study. In the specific case study, the authors obtained slightly more interesting results and analysis based on the RSM. The greater picture of the methodology implementation is considered to be the same.

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BIOGRAPHIES

Vasileios D. Sagias graduated from the Mechanical Engineering Department of Piraeus University of Applied Sciences in Athens, Greece, in 2004. He holds a Master of Science degree in Advanced Industrial and Manufacturing Systems from Kingston University, UK, at which he is currently a PhD student. He has had 15 years' experience, mainly in the quarrying machine industry, in the fields of mechanical design, CAD (2D and 3D), CAE, CAM, CNC, CAD customisation using API, but also in production and inventory management. He started his career as a mechanical designer, which has led to his appointment as Head of Design-R/D Department. Also, for the past 10 years, he has been working as a safety engineer and is currently an Adjunct Professor at Piraeus University of Applied Sciences, Piraeus-Athens, Greece. His teaching-laboratory experience is mainly in mechanical design, CAD, CAE, CAM and production management related modules. His research areas include adaptive meshing techniques, CAD technologies corresponding with numerical methods (such as BEM and FEM) and design of experiments.

Prof. Dr-Ing. Constantinos Stergiou received his mechanical engineering degree from the National Technical University Athens, Greece and his PhD from the Technische Universität Darmstadt, Germany. He is a Professor at Piraeus University of Applied Sciences, and is the Head of the Mechanical Engineering Department. He has been an Honorary Professor at Kingston University London - Faculty of Science, Engineering and Computing since May 2013. In 2002, he organised and became the Academic Director of the MSc in Advanced Industrial and Manufacturing Systems, a collaboration with the Faculty of Science, Engineering and Computing of Kingston University, London, UK. He has professional experience at technical bureaux and research projects. He lectures in engineering design and computer-aided design, and has written eight books, most of which are the official handbooks given out to engineering students at various universities and TEI across Greece. He has organised training programmes for manufacturing plants in countries in and outside Europe. He has had over 65 papers published in international journals and conference proceedings, is supervising four PhD students and has supervised 65 MSc theses, 25 BSc theses and 50 industrial experience semester students.

Redha Benhadj-Djilali is a chartered engineer, member of the Institution of Mechanical Engineers and member of the British Computer Society. He specialises in CAD/CAM/CAE, engineering design and manufacturing automation, and has been at Kingston University since 1994. He worked in the manufacturing industry before starting his academic career at Kingston University, where he also held a research fellowship and, then, a lecturer position. His research project was based on the development of a pneumatic array of air jet proximity to tactile sensing device for manufacturing parts identification, slip detection and force monitoring. He also held a research fellowship for more than two years, and during that time, he was involved in promoting research in manufacturing automation and assembly. He also carried out further research in the application of the tactile sensing device to monitor slip and gripping force to assist robot part handling and assembly. He is on the editorial boards of three international journals: Sensor Review, Industrial Robots and Assembly Automation, and reviews other international journal and conference papers. His research interests are in the fields of design and manufacture, advanced CAD/CAM, robot tactile sensing and AI.

Evangelos Ganiaris was awarded a Bachelor's degree in mechanical engineering at Piraeus University of Applied Sciences, Piraeus-Athens, Greece, in 2011, where he also contributed when he worked as an auxiliary educational staff member during his internship at the CAD laboratory. A year later, he was accepted into the Master's programme in Advanced Industrial and Manufacturing Systems (AIMS) of Kingston University, London, UK. He was elected the student representative of the MSc AIMS class of 2014 at the board meetings of the University and he was awarded his degree with distinction. During his Master's thesis programme, he took part in research work, part of which is presented in this article. Currently, he works as a technical sales engineer, representing the Viohalco Group of Companies, which accounts for approx. 9% of Greece's total exports in the markets of Central Europe.