Journal Paper

Independent Assessment and Benchmarking of no/low cost Finite Element Analysis Software for Linear Static Structural Analysis

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This work assesses no and low cost FEA software. The work is most relevant for businesses or individuals who are not able to afford the industry standard proprietary FEA packages; this paper might aid them in selecting a lower cost alternative while maintaining a level of confidence in the results. The investigation was undertaken for both linear and nonlinear static structural analyses using isotropic material models, but due to the volume of content, only the findings for linear static modelling are presented here.

Abstract: The aim of this work was to determine if the development of low-cost or no-cost finite element analysis (FEA) software has advanced to the point where it can be used in place of trusted commercial FEA packages for linear static structural analyses using isotropic material models. Nonlinear structural analysis will be covered in a separate paper. Several suitable packages were identified, these underwent a process of systematic elimination when they were unable to meet the minimum imposed qualitative criteria. Three packages were chosen to be subjected to performance benchmarking, namely: Code_Aster/Salome Meca; Mecway and Z88 Aurora. SimScale, a browser-based analysis package was included as well because it met all the baseline criteria and has the potential to offer a completely cloud-based approach to computer aided engineering, potentially reshaping the way an engineering business views its operational capabilities. This paper presents the test cases and simulation results for packages that fall under the linear static structural analysis type.

Keywords: Open source; FEA; finite element analysis; linear static structural; Code_Aster; Salome Meca; Mecway; SimScale; Z88, CAE

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1. Introduction

The rapid increase of computational power over the past few decades has been a catalyst for change in various industries. Software developers are able to take advantage of increasing computational power and can create numerical modelling packages capable of dealing with a progressively larger range of physical problems [1]. Consequently, increasing confidence is being placed in the results of computational simulations [2].

The increasing acceptance of computational analysis results has created a problem. Software developers have been pushed to improve their packages capabilities, which subsequently increases costs. The cost of trusted proprietary numerical modelling packages is generally significant and, in some cases, exorbitant. These packages are typically used by large companies or research

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institutions with the resources to acquire them. The inability to readily acquire these numerical modelling software packages puts small to medium sized design and manufacturing companies at a disadvantage, as it limits their operational capabilities. Fortunately, there have been a growing number of small proprietary software developers as well as an active open source development community, creating and improving relevant software packages in fields such as CFD and FEA. These can potentially be used in place of the expensive commercial proprietary packages. This paper concisely presents the findings from a master's dissertation completed by the first author. The research aimed to determine if the development of low-cost/no-cost software packages, specifically in the field of FEA in computational structural mechanics (CSM), has advanced to the point where a capable analyst can confidently use one of these packages in place of a globally trusted proprietary FEA software package for linear and nonlinear static structural analyses using isotropic material models. Due to the volume of content, the research has been split into two papers. This paper only presents the findings for linear static analysis modelling; a future paper will present the findings related to nonlinear static structural analysis problems.

2 The Impact of FEA on Industry

The advancement in capabilities of simulation software over the past two decades has significantly changed the way in which product conceptualization and design is viewed. Looking specifically at the advancement in FEA software, it has allowed for significant innovation and the development of accurate design methods at drastically reduced cost [3].

With the increase in the capability and fidelity of commercial software, FEA has influenced a new market trend in industry. The term "simulation-driven product development" is commonly used to describe the integration of simulation software into the early design process and basing decisions on simulation results [4].

Evidence to validate the above statement can be found in a relevant report titled "The 2013 State of Simulation Design" [2]. The aim of the report was to answer the following question: "Are today's engineers making decisions based on simulations?" The findings of the report were based on survey responses from 826 respondents from a wide range of industries worldwide. The majority of the respondents were from the automotive, industrial equipment manufacture, aerospace and defence industries [2]. The survey focused mainly on how respondents used simulation to drive decisions during the concept design phase, as well as in the more detailed design phase.

There are many adverse effects caused by failed prototypes and concept designs. Many of these waste time and resources and could potentially cause the termination of a design project. Key business value findings showed that best-in-class manufacturers will need to hit roughly 86% of their cost and release targets while releasing 1.6 fewer prototypes than competitors on average [5]. In excess of 70% of respondents stated that simulation results are used to select or improve concept designs [2]. When looking at the more detailed design phase, more than 75% of the respondents stated that simulation is used to refine or select ideas. Through simulation based design refinements, companies were able to better determine correct sizing and appropriate material selection, which in turn drives production costs down. The results of the survey indicated that less than 10% of the respondents within major engineering fields did not make use of any simulation during their design process.

Simulation techniques such as FEA and CFD have become an industry standard. Taking these figures into account, it is evident that the majority of industries are using computational simulations to drive design and manufacture, therefore significant cost savings can be incurred by acquiring capable no-cost/low-cost simulation software to replace existing high cost industry-standard options, particularly for small to medium sized companies who may not perform as frequent simulation, and for whom software costs likely make up a larger proportion of their expenses.

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Looking at the implementation of no-cost/low-cost software in the context of a small business, it would allow for previously unobtainable resources to become a part of regular operational capabilities, likely making the business more competitive and relevant in the modern market.

3. Methodology

3.1 Software identification and selection

Research allowed for the identification of several low-cost/no-cost FEA software packages. Choosing a limited number of no-cost/low-cost packages that pass certain baseline criteria before proceeding to the performance benchmarking phase of the research aided in streamlining the entire process. The basis of the chosen selection criteria was guided by anticipated industry requirements. It was based on both research and on discussion and hands-on experience, with two of the authors operating a small mechanical engineering consultancy previously utilising both industry standard and free software. The selection procedure implemented is illustrated in Figure 3-1.

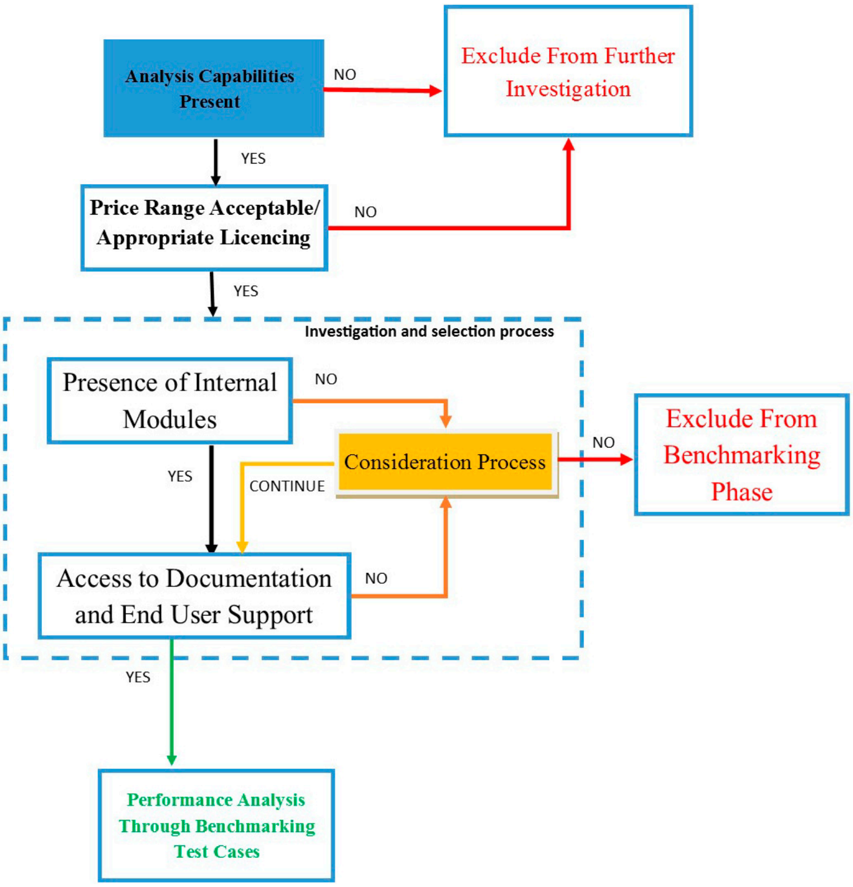

Figure **Error! No text of specified style in document.**-1. Package selection procedure

The inability to perform the required type of analysis immediately excluded a package from further investigation. The price of the package and licencing approach was considered. If the package was 'expensive' (chosen to be greater than 500 USD per year as initial cost of purchase) or licenced such that it prohibits the use of the package commercially, it was excluded. If a package passed the aforementioned criteria, the presence of the internal modules were checked.

The lack of either a pre-processor or a post-processor did not immediately exclude the package. It resulted in the package going into a consideration process. A judgement was made based on the ability of the solver to accept various imported file formats as well as export post-processing file formats from commercial packages as well as other low-cost/ no-cost packages. If a package was

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deemed to be capable with respect to file type compatibility, the documentation and user support was investigated. If it appeared that no user support was readily available then the package would return to the consideration process. If it was deemed that the package was not user friendly (via either the interface itself or documentation or support) as well as lacking a pre or post-processor, it would be excluded from the following phase of the research.

The selection of two premium commercial packages was done for quantitative and qualitative comparison between what is considered a premium package and the chosen no-cost/low-cost packages. The selection of commercial FEA software was based on software availability at the University of KwaZulu-Natal.

3.2 Review and Selection of Benchmarking Test Cases

Appropriate benchmark tests cases were selected to be simulated within the chosen packages. This process began by investigating the verification manuals of renowned, commercially available FEA software packages. This revealed that the leading software developers verify their codes through a benchmarking process that utilizes well-known analytical solutions as well as examples from trusted benchmark publications. The benchmark publishers referenced were the National Agency for Finite Element Methods and Standards (NAFEMS) and Société Française des Mécaniciens.

With this knowledge, a variety of test cases were selected that fell within the scope of this research. Test cases were separated into analytical problems with known solutions and benchmark standards. A final test case was based on experimental data from physical laboratory testing. This will be discussed in a future paper discussing the nonlinear analysis testing.

Selection of the test cases was based on the test case falling within static structural analysis, the problem geometry and loading conditions being easily repeatable, and the potential for the problem to be readily tested and validated experimentally. The selected test cases are presented in section 5.

3.3 Solution of Test Cases Using Selected Software

The chosen packages were subjected to the selected test cases. The simulation process used for the test cases can be seen in Figure 3-2. The result was analysed and classified within one of three result categories.

The first category, "Realistic results, acceptable accuracy", would see the solution exhibiting the expected response to the loading and constraints, with the value of the solution strongly correlating to expected values stipulated by the test case.

Research was conducted to determine what the industry accepted measure of 'accuracy' is. There is no agreed upon value as it appears that 'accuracy' is very application-specific. Trusted discussion forums show claims from industry analyst that inaccuracies up to 10% for linear static examples are acceptable for certain applications. Others report that for some complex examples, such as analyses involving material non-linearities or contact problems, errors may commonly be as high as 20% [6]. For the purpose of this research, accurate solutions must fall within 5% of the target solution. This value is lower than what industry analysts suggest because the benchmarking analyses selected are not considered highly complex and a capable FEA package should thus be able to readily generate solutions with greater accuracy than for more complex systems.

The second category, "realistic results, unacceptable accuracy", pertains to situations when the solution exhibited the expected response but yielded a solution with unacceptable accuracy. This would indicate that the boundary conditions were likely correctly implemented. To address the inaccuracy in the solution, the mesh parameters or mathematical model used to solve the model should be re-evaluated. This loop can be run until satisfactory results are obtained.

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The third category, "unrealistic results", pertains to situations where results generated do not exhibit expected response to the loading conditions or yield grossly inaccurate numerical values. This phenomenon could be attributed to various factors. In such cases it is advised to revisit the various aspects of the model construction, as shown in Figure **Error! No text of specified style in document.**-2 and verify that these aspects represent the physical system being modelled as closely as possible. This loop can be run until satisfactory results are obtained.

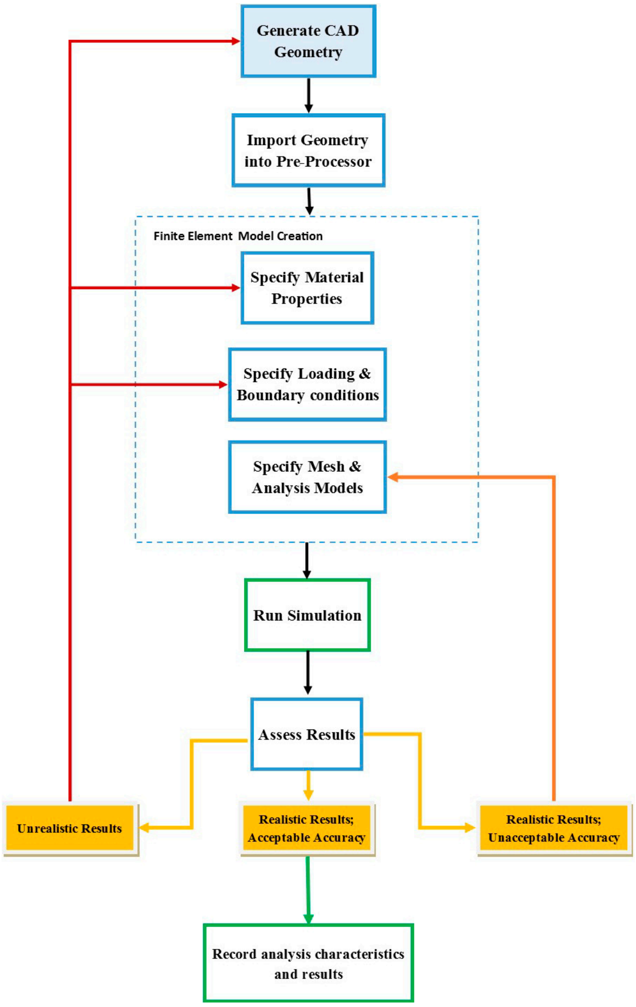

Figure **Error! No text of specified style in document.**-2. Computational simulation process

This validation phase assessed the performance of the selected packages. Results for each test case with each package were gathered and processed. The results were compared against expected theoretical solutions so that a gauge of accuracy could be obtained.

4. Selected software

Using the selection procedure discussed in Section 3, three no-cost/low-cost packages were selected to be investigated further. A no/low-cost web-based simulation platform was added to the selection.

- Code Aster is a freely available open source, Linux-based solver package commonly used in civil and structural engineering. It is most commonly used through Salome Meca, which acts as the GUI for pre and post-processing. It was developed by the French company, EDF and the software and documentation was previously only maintained in French [7], but the software is now available in English with poorly machine translated documentation available. Salome Meca is a very compartmentalized application and requires users to load separate modules in order to import and prepare geometry, create a suitable mesh and finally to view the results. The actual computation of the finite element solution happens through Code_Aster. The user must be well versed in the scripting language readable by the Code_Aster solver. The user must be able to code the aster file so that the correct analysis type, material models, loads and constraints are all incorporated. There is a significant learning curve and it does prove quite complex to new users.

- Mecway is an inexpensive Windows-based package that allows users to solve various engineering problems using the finite element method [8]. The user interface has many of the characteristics found in trusted commercial packages. A single licence costs 99 USD per year.

- Z88 is a free, cross platform package that can be used for the solution of various engineering problems through numerical simulation by the finite element method. There are 2 versions currently available. Z88 V14, an open source version lacking a pre-processor, and Z88 Aurora, a freeware version with built-in pre-processor [9].

- SimScale is a web-based simulation platform for the solution of certain physics problem types through numerical methods. SimScale has the analysis capabilities to provide solutions to 3-D problems only, in structural analysis, thermodynamics and heat transfer, CFD, particle analysis, acoustics as well as coupled multiphysics problems. Lower dimension problems are not currently solvable. A free account can be created which entitles the user access to the full range of analysis capabilities. Paid users have access to priority computing resources as well as a direct line of contact with SimScale consultants[10].

Table 4-1 through to Table 4-4 present various aspects of the investigated packages.

Table Error! No text of specified style in document.**-1.** Analysis capabilities

Package	Linear Static Structural	Non-Linear Static structural	Multi-body Contact	Dynamic structural	Composite structural
Code_Aster/Salome-meca	✓	✓	✓	✓	✓
Mecway	✓	✓	✓	✓	✓
Z88 Aurora	✓	✓	x	x	x
SimScale	✓	✓	✓	✓	x

Table Error! No text of specified style in document.**-2.** Operating systems

Package	Linux	MS Windows	MAC OSX
Code_Aster/ Salome-meca	✓	✓	x
Mecway	x	✓	x

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Z88 Aurora	✓	✓	✓
SimScale	Does not depend on Operating system		

Table Error! No text of specified style in document.**-3.** File type compatibility

Package	Import	Export
Code_Aster/ Salome-meca	Generated mesh files and CAD files of various formats.	Code_Aster generates a MED file which can be exported to Salome Meca or any other compatible post-processing software
Mecway	CAD geometry import: .iges, .step. Generated mesh files e.g. Gmsh, NetGen.	Can export result files in VRML format to graphical processing tools to generate contour plots.
Z88 Aurora	CAD geometry import capabilities Generated mesh files.	Allows for FE structure data such as ANSYS, NASTRAN and ABAQUS files to be exported.
SimScale	CAD imports through .step files	Result files can be exported to 3rd party postprocessors eg Paraview.

Table Error! No text of specified style in document.**-4.** Pricing

Package	Price
Code_Aster/ Salome-meca	Free
Mecway	USD 99.99 per year per licence.
Z88 Aurora	Free
SimScale	Free / Monthly payment of 200 USD

5. Results and Discussion of Linear Static Structural Analysis test cases

Several sources were initially considered and many potential test cases were identified. The following cases were chosen from amongst the available possibilities as they would test a range of analysis capabilities with respect to static structural analyses, with minimal repetition of model types.

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5.1 Point Load on an Articulated Truss

This test case was taken from an industry accepted standards publication [11]. This test is a 2-D linear static analysis of 1D truss. Figure 5-1 presents the 1D line geometry for this test case.

Table Error! No text of specified style in document.**-5** shows the information associated with this test case.

Table Error! No text of specified style in document.**-6** presents the target solutions for this test case as given in test case.

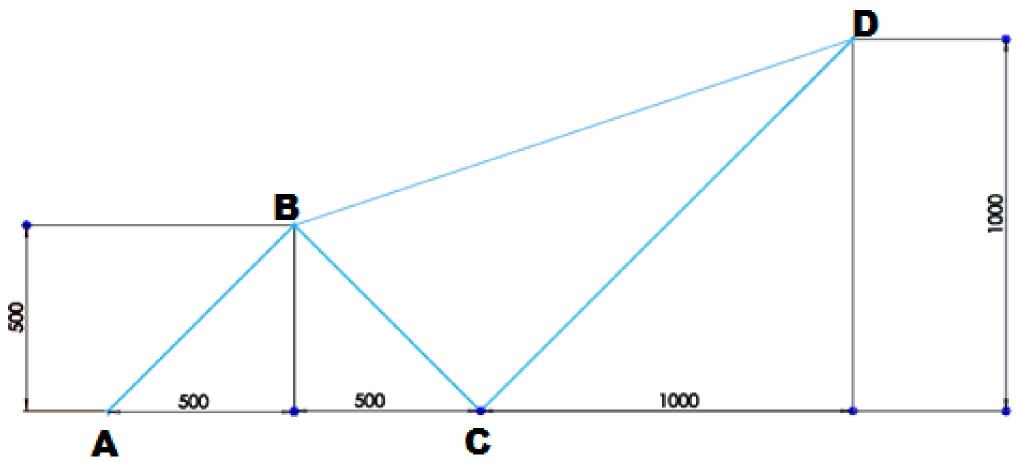

Figure Error! No text of specified style in document.**-3.** Truss system geometry [11]

Table Error! No text of specified style in document.**-5.** Input parameters for truss analysis problem.

<table>
<tr><td>Material Properties</td><td colspan="2">E = 1.962 E+11 Pa</td></tr>
<tr><td rowspan="3">Geometrical Properties</td><td>Element</td><td>Area (m²)</td></tr>
<tr><td>AB & BC</td><td>2 E-4</td></tr>
<tr><td>BD & CD</td><td>1 E-4</td></tr>
<tr><td rowspan="4">Boundary Conditions</td><td>Node</td><td>Constraint/Load</td></tr>
<tr><td>A</td><td>Zero X and Y displacement</td></tr>
<tr><td>B</td><td>Zero X and Y displacement</td></tr>
<tr><td>D</td><td>Force = 9810 N in -Y direction</td></tr>
</table>

Table Error! No text of specified style in document.**-6.** Target solutions for truss problem.

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Node point	Target	Benchmark Value (m)
C	X - displacement	0.26520 E-3
C	Y - displacement	0.08839 E-3
D	X - displacement	3.47900 E-3
D	Y - displacement	-5.60100 E-3

To successfully model this test case, the suggested approach was to import the geometry to the pre-processor or create it within the pre-processor, and assign the two required truss element types as applicable. The prescribed boundary conditions must be applied to the relevant nodes. Finally, the post-processing module of the package must be able to represent the target solutions on an appropriate plot.

Simulation Results

Table Error! No text of specified style in document.**-7** contains the results for this test case. Note that results are presented for individual nodes.

Table Error! No text of specified style in document.**-7.** Results for Point Load on an Articulated Truss Test Case

Node	Target [m]	Benchmark Value	Deviation				
			Mecway	**Z88**	**Code_Aster**	**ANSYS**	**NX**
C	X - displacement	0.26520 E-3	50.10%	19.10%	36.30%	49.15%	9.35%
	Y - displacement	0.08839 E-3	0.00%	0.01%	4.03%	0.00%	0.44%
D	X - displacement	3.47900 E-3	0.00%	0.03%	0.03%	0.00%	0.00%
	Y - displacement	-5.60100 E-3	0.02%	0.02%	0.03%	0.01%	0.02%

Note that SimScale is unable to perform analyses on 1-D geometry at this stage of its development. The remaining packages were able to generate the model in the suggested approach and yield appropriate displacement results through a graphical postprocessor. It is seen that the no-cost/low-cost options as well as the commercial packages all yielded results with large deviations from the target solutions for the X-direction displacement at Node C. Bearing in mind that the benchmark target solutions are performed computationally, it might indicate the possibility of an inaccuracy in the target solution, but would not explain the difference in deviation from 9% to 50%.

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All other results fell within an acceptable deviation. All employed packages dealt well with the model generation and offered intuitive node-element creation tools.

5.2 Thin Shell Wall in Pure Bending

This test case was taken from the engineering text, "Mechanical Engineering Design" [12]. This test case is a 3-D linear static analysis which investigates the maximum deflection and stress in an edge loaded wall, which is represented as a 2-D shell for analysis. Figure Error! No text of specified style in document.**-4** shows the geometry of the 2-D shell representation of the geometry. Table Error! No text of specified style in document.**-8** shows the information associated with this test case. Table Error! No text of specified style in document.**-9** presents the target solutions for this test case as given in test case.

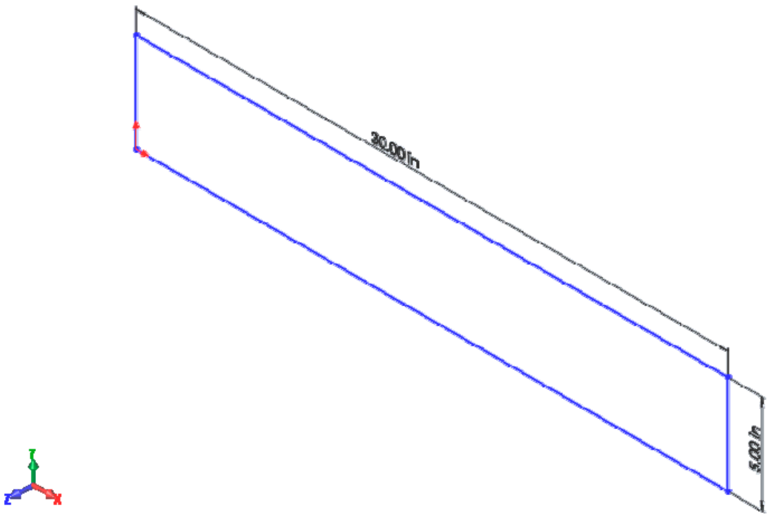

Figure Error! No text of specified style in document.**-4.** Wall geometry represented as a 2-D shell [12]

Table Error! No text of specified style in document.**-8.** Input parameters for wall problem.

Material Properties	E = 30 E-6 psi
	ν = 0.03
Geometric Properties	Length = 30 in
	Width = 5 in
	Thickness = 0.1 in
Boundary Conditions	Zero displacement for edge situated at the origin
	Edge load = 6 lbf on remaining upright edge

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Table Error! No text of specified style in document.**-9.** Target solutions for wall problem.

Target	Benchmark Value
Maximum Z Deflection	4.320 in
Maximum Z Stress	2.160 E+4 psi

To successfully model this test case, the suggested approach was to import a 2-D shell geometry into the pre-processor of the package. An appropriate 2-D element must be used to mesh the geometry and the stipulated material properties must be assigned. The pre-processor must be used to stipulate the required boundary conditions. The post-processing module for the package should be used to represent the target solutions on appropriate plots.

Simulation results

This test case was run several times, refining the mesh each time, while keeping other variables constant. The results presented in Table Error! No text of specified style in document.**-10** are those of the result set with the finest mesh size of 0.15 in. Results tended towards greater accuracy with decreasing mesh size.

Table Error! No text of specified style in document.**-10.** Results for Thin Shell Wall in Bending Test Case

Point	Target	Benchmark Value	Deviation			
			Mecway	**Code_Aster**	**ANSYS**	**NX**
Loaded Edge	**Maximum Z Deflection**	**4.320 [in]**	**1.64%**	**0.02%**	**0.02%**	**0.02%**
Fixed Edge	**Maximum Z Stress**	**2.160 E+4 [psi]**	**5.69%**	**0.18%**	**0.18%**	**0.00%**

SimScale is unable to perform analyses on 2-D bodies at this stage of its development. Z88 Aurora was unable to produce a suitable 2-D mesh to discretize the geometry. Attempts were made to use a 3-D mesh to discretize the model, however a suitable mesh was not able to be generated in either SimScale or Z88 Aurora. The remaining packages were able to yield results that fell within acceptable accuracy, apart from the stress value yielded by Mecway.

5.3 Axisymmetric Pressure Vessel

This test case was taken from an industry accepted publication "The NAFEMS Standard Benchmarks" [13]. This test case, labelled LE7 in the publication, is a linear static analysis of a cylindrical pressure vessel with spherical end caps. Due to the geometrical symmetry of the model, it can be modelled as a 2-D axisymmetric surface.

Figure Error! No text of specified style in document.**-5** below shows a 2-D axisymmetric representation of the pressure vessel presented in millimetres

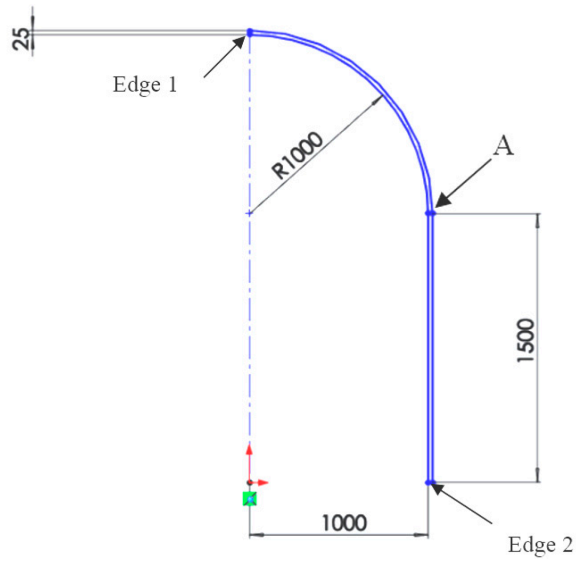

Figure Error! No text of specified style in document.**-5.** Axisymmetric representation of pressure vessel [13]

Table Error! No text of specified style in document.**-11.** Input parameters for axisymmetric pressure vessel test case.

Material Properties	E = 2100 MPa
	ν = 0.3
Geometric Properties	Axisymmetric 2-D Shell with given dimensions
Boundary Conditions	Edge 1 – Zero X-Displacement
	Edge 2 – Zero Y-Displacement
	Uniform internal pressure = 1 MPa

Table Error! No text of specified style in document.**-12.** Target solutions for axisymmetric pressure vessel analysis problem

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Target	**Benchmark Value**
Axial Stress σ(yy) on outer surface at specified point	25.86 MPa

To successfully analyse this test case, the suggested approach was to import the 2-D geometry into the pre-processor. It would be ideal if the package had a dedicated 2-D axisymmetric analysis option available. The pre-processor should be used to specify 2-D elements with the required material properties assigned. The boundary conditions should be applied in a manner that correctly represents the axisymmetry present. The target solution requires a specific directional stress and hence the solver should be able to compute this stress value. Lastly, the post-processing module for the package must be used to represent the target solution on an appropriate plot.

Simulation results

This test case was run several times, refining the mesh while keeping other variables constant. The results presented in Table Error! No text of specified style in document.**-13** are those of the result set with the finest mesh size of 5mm. Results tended towards greater accuracy with decreasing mesh size.

Table Error! No text of specified style in document.**-13.** Results for axisymmetric pressure vessel analysis problem

Point	Target	Benchmark Value	Deviation					
			Mecway	**Z88***	**Code_Aster**	**SimScale***	**ANSYS**	**NX**
Prescribed outer surface point	Axial Stress σ(yy)	25.86 [MPa]	0.23%	4.41%	0.04%	2.39%	0.03%	0.54%

As mentioned before, SimScale was unable to perform analyses on 2-D bodies at this stage of its development. Z88 Aurora was unable to produce a suitable 2-D mesh to discretize the geometry. Attempts were made to use a 3-D quarter geometry model to analyse problem for both SimScale as well as Z88 Aurora (*). In both cases a coarse mesh could be used to yield results, however the software crashed when mesh refinement was attempted as the number of elements became excessively high.

All packages were able to yield results of acceptable accuracy. Mecway, Code_Aster, ANSYS and NX all possess dedicated axisymmetric analysis environments which assisted in streamlining the model generation phase and in producing accurate results.

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5.4 Internal Pressure on Thick-Walled Spherical Container

This test case was taken from an industry-accepted standards publication titled, "*Guide de validation des progiciels de calcul des structures*" [11]. This test labelled SSLV 03/89 is a 3-D linear static analysis of a thick-walled spherical vessel experiencing an internal pressure loading. Due to the geometrical symmetry, the vessel can be modelled as a quarter sphere as seen in Figure Error! No text of specified style in document.**-6**. Dimensions are presented in millimetres

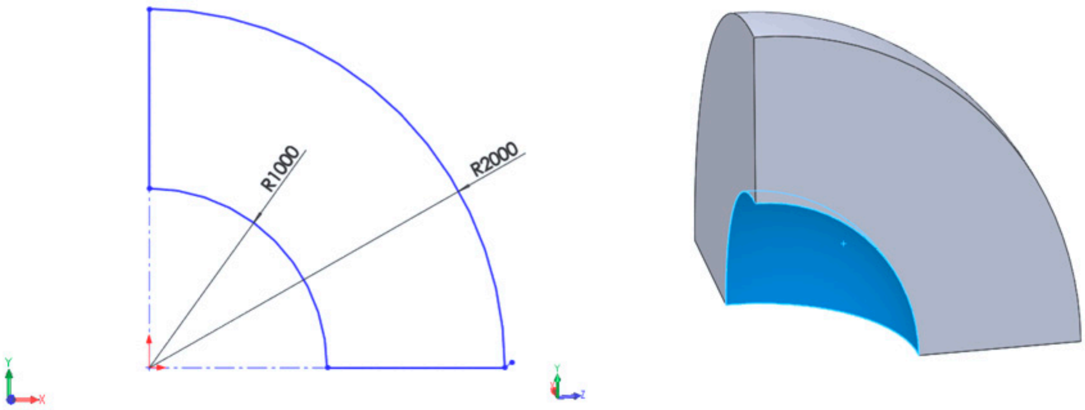

Figure Error! No text of specified style in document.**-6.** Quarter sphere geometry [11]

Table Error! No text of specified style in document.**-14.** Given information for spherical pressure vessel analysis problem

Material Properties	E = 200 MPa
	ν = 0.30
Geometric Properties	Quarter spherical geometry with specified dimensions
Boundary Conditions	Symmetry conditions apply at orthogonal flat faces
	Uniform internal pressure = 100 MPa

Table Error! No text of specified style in document.**-15.** Given target solutions for spherical pressure vessel analysis problem.

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Results : Internal Surface		**Results : External Surface**	
Target	**Benchmark Value**	**Target**	**Benchmark Value**
σ_{rr}	**-100 MPa**	**σ_{rr}**	**0.00 MPa**
σ_{θ}	**71.43 MPa**	**σ_{θ}**	**21.43 MPa**
u	**0.4 E-3 m**	**u**	**0.15 E-3 m**

To successfully analyse this test case, the suggested approach is to import the 3-D quarter sphere geometry into the pre-processing module of the package. The pre-processor must be used to assign appropriate mesh elements for the model. The symmetry conditions must be properly represented using appropriate constraints. The pressure loading must be applied on the appropriate curved face. Noting that the target solution requires two directional stresses as well as a displacement, the solver should be able to solve for these results. Lastly, the post-processing module for the package must be used to represent the target solution on an appropriate plot.

Simulation results

This test case was run several times refining the mesh, while keeping other variables constant. The results presented in Table Error! No text of specified style in document.**-16** are those of the result set with the finest mesh size of 50 mm. Results tended towards greater accuracy with decreasing mesh size.

Table Error! No text of specified style in document.**-16** Results for Spherical pressure vessel analysis problem

Results : Internal Surface							
Target	**Benchmark Value**	**Deviation**					
		Mecway	**Z88**	**Code_Aster**	**SimScale**	**ANSYS**	**NX**
$\sigma(rr)$	-100.0 [MPa]	0.90%	-	0.16%	0.14%	0.13%	4.37%
$\sigma(\theta)$	71.43 [MPa]	1.10%	-	1.29%	1.37%	0.05%	2.86%
u	0.400 E-3 [m]	0.10%	0.10%	0.00%	0.25%	0.00%	0.00%
Results : External Surface							

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Target	Benchmark Value	Deviation					
		Mecway	**Z88**	**Code_Aster**	**SimScale**	**ANSYS**	**NX**
σ(rr)	**0.00 [MPa]**	3.23 MPa	-	1.225 MPa	0.175 MPa	0.012MPa	0.28 MPa
σ(θ)	**21.43 [MPa]**	1.02%	-	0.35%	0.42%	0.08%	0.65%
u	**0.150 E-3 [m]**	0.00%	0.00%	0.66%	0.66%	0.00%	0.00%

All packages besides Z88 were able to solve for the appropriate stresses and displacements. Z88 was unable to solve for the required principle stresses. We see that the packages were able to yield results of acceptable accuracy where applicable.

5.5 Flat Bar with Stress Concentration

This test case was developed based on empirical models found in the Engineering Text "Mechanics of Materials" [14]. This test case is a 3-D linear static analysis of a flat bar with stress concentrations under a tensile load. Figure Error! No text of specified style in document.**-7** below shows the chosen geometry for this test case presented in millimetres.

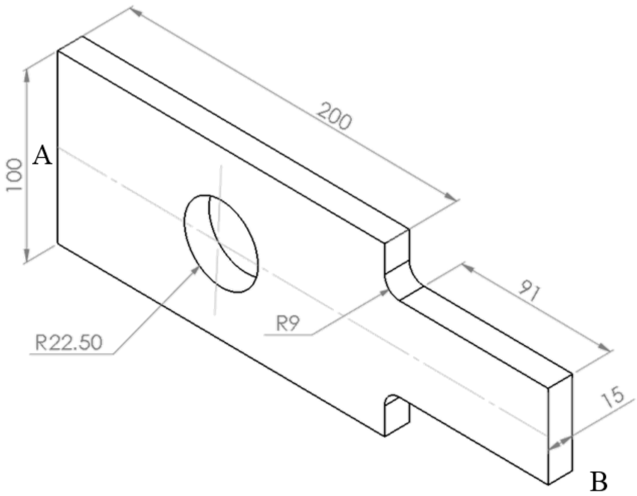


Figure Error! No text of specified style in document.**-7.** Geometry of flat bar with stress concentrations

Table Error! No text of specified style in document.**-17.** Properties to be used for the flat bar with stress concentration analysis problem.

• **Material Properties chosen**	• **E= 210 GPa**
	• **ν = 0.3**

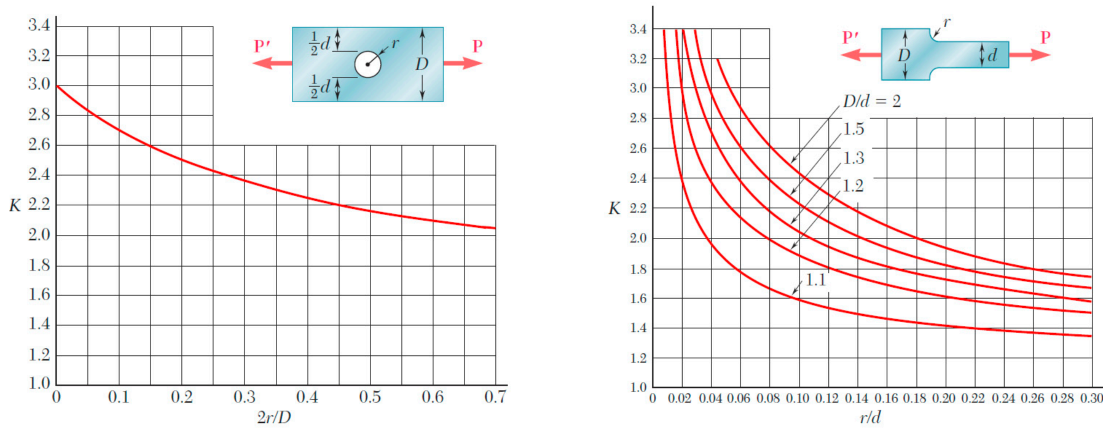
• **Geometric properties chosen**	• **Dimensions as specified in mm**
	• **Thickness = 15 mm**
• **Boundary conditions chosen**	• **Zero translation at face A**
	• **Normal force = 1000 N at face B**

Results calculated:

$$\sigma_{max} = K \left(\frac{F}{A}\right) \quad \textbf{(5.1)}$$

Where σ_{max} represents Maximum stress, K represents the Stress concentration factor ; F is the Applied Force and A is the Cross Sectional Area

Using Stress concentration factors for flat bars under tensile loading from [14] in Figure Error! No text of specified style in document.**-8** , K_{hole} and K_{fillet} were obtained.



(*a*) Flat bars with holes (*b*) Flat bars with fillets

Figure Error! No text of specified style in document.**-8.** Stress concentration factors for flat bars under tensile loading [14].

From Figure Error! No text of specified style in document.**-8** (a) it was determined,

$$\sigma_{hole} = 2.667\ MPa$$

And,

$$\sigma_{fillet} = 2.667\ MPa$$

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Table Error! No text of specified style in document.**-18.** Calculated results for the flat bar with stress concentrations analysis problem.

Point	Target	Benchmark Value
Fillet	**Maximum Stress**	**2.66 MPa**
Hole	**Maximum Stress**	**2.66 MPa**

To successfully model this test case, the 3-D geometry would need to be imported into the pre-processer of the FEA package. The appropriate material properties and a suitable mesh should be applied. The loading and boundary conditions must be applied to the relevant faces of the model. The post-processor of the FEA package must be used to output the target solution on an appropriate plot.

Simulation results

This test case was run several times refining the mesh, while keeping other variables constant. The results presented in Table Error! No text of specified style in document.**-19** are those of the result set with the finest mesh size used, 1.5 mm. Results tended towards greater accuracy with decreasing mesh size.

Table Error! No text of specified style in document.**-19.** Results for flat bar with stress concentration analysis problem

Point	Target	Benchmark Value	Deviation					
			Mecway	**Z88**	**Code_Aster**	**SimScale**	**ANSYS**	**NX**
Hole	X - Stress	2.66 [MPa]	3.75%	2.25%	0.75%	0.75%	1.88%	1.88%
Fillet	X - Stress	2.66 [MPa]	3.75%	2.25%	0.75%	0.75%	1.88%	1.88%

All packages were able to yield usable results within an acceptable accuracy.

6. Conclusion

FEA is widely incorporated into multiple stages of engineering design and important decisions are made based on FEA results, significantly improving design efficiency. Bearing this in mind, it is evident that this work may have a tangible financial impact on businesses or individuals wishing to integrate affordable FEA into their operational capabilities.

The work endeavoured to determine whether no-cost or low-cost FEA packages have advanced to the point where they can be utilised and relied on in a similar manner to trusted commercial FEA packages for linear static structural analyses of varied geometries using isotropic materials. The chosen packages were all subjected to the same benchmarking test cases and the modelling

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procedure directed by a standardised approach. This procedure was adhered to unless impossible to accomplish within a specific package. With the modelling procedure standardised, the control variable was the mesh element size. Mesh refinement was performed during the test with the intent of obtaining mesh independence. Mesh size was reduced until it was observed that no significant change in target solution was obtained

Looking at the overall performance of Mecway, it can be said that this package offers excellent value for money. It possesses a user-friendly interface and the layout ensures a systematic approach to model generation that mitigates the chance of omitting any steps. It was adequately capable when dealing with the test cases. Linear elastic cases were routine and the results showed good accuracy relative to both the test case target solutions as well as to the premium packages used. Mecway also has the ability to conduct several other analysis types such as vibrational analysis, electrostatic and thermal analysis, among others. For linear structural analyses using isotropic materials, Mecway can integrate seamlessly into the operational capabilities of an established company looking to replace their high-cost commercial package. It would also be useful in academic institutions for the purpose of supporting the education of students in the process of FEA.

Z88 Aurora was limited by its pre-processor capabilities. The interface is acceptable but the manner in which a model is created feels laborious at times. Possibly the biggest shortcoming is the inability for Z88 Aurora's pre-processor to generate a suitable 2-D mesh. It is possible to import mesh files, but that goes against the convenience of being an all-inclusive FEA package option. That being said, it was adequately capable when dealing with 3-D geometry, apart from being unable to solve for directional stresses. Results that were generated showed good accuracy relative to both the test case target solutions as well as to the premium packages. All things considered, it would be difficult, at this stage of development, for Z88 to be used in place of a trusted commercial package for linear static structural FEA. In its current state of development, Z88 Aurora would be a good tool to implement at academic institutions for teaching purposes.

Using Code_Aster/Salome Meca was a daunting task initially, it functioned differently to other contemporary FEA packages. Salome Meca requires users to be well versed with a package-specific model generation procedure. The pre-processing procedure is highly modular in that each stage requires a specific module and its environment to be loaded. This does give a very systematic and structured model generation procedure. The fact that there is such a significant library of functions available may appear intimidating at first, but with some training and understanding, the model customization potential associated with Code_Aster is immense. With some effort, Code_Aster is capable of serving a user significantly better than many entry to mid-level commercial FEA packages. The model generation capabilities and result accuracy relative to the target solutions and premium packages, have led to the conclusion that Code_Aster/Salome Meca can be used in placed of a trusted commercial package for linear static structural FEA.

SimScale was found to be a capable package, other than its inability to deal with 1-D and 2-D elements. The web-based interface is appealing. It has the tools and capabilities that would be expected from commercial FEA packages. With a free account, a user is entitled to all of the analysis capabilities that a paid user has, apart from a direct line of contact with the developers. Using SimScale with OnShape, a free-to-use web-based parametric design modeller, allows for a completely cloud-based approach to computer aided engineering, removing the need for costly computational infrastructure. The results yielded by SimScale showed good accuracy relative to both the target solutions as well as to the premium software packages. With the developer's promise of lower-dimensional analysis capabilities being in progress, this makes SimScale a viable candidate for use in place of trusted commercial packages for linear static structural FEA. It must be noted however, that basing one's operational capabilities on web-based CAE packages has an obvious drawback. The user is vulnerable to the possibility that the service may be interrupted or even terminated in the future, and vulnerable to lack of internet connectivity. Incorporating SimScale into

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commercial operations should therefore be approached with some consideration. It would possibly be wise to possess another no-cost/low-cost option as a contingency in case SimScale's services are interrupted.

Overall, it has been shown that there are no-cost/low-cost options for users wishing to avoid the high cost of premium commercial FEA packages for the analysis of linear structural problems with isotropic materials. It must be stated that this research has not sought to determine whether any of the investigated packages are better or worse overall than a given premium commercial package. If the resources are available to acquire a premium package, it would be advised to do so, as these packages have been refined to a point where model generation is highly streamlined and they include extended tools, capabilities and backup that are often invaluable. Their high cost is certainly justifiable if a comprehensive multi-physics analysis package is required, or depending on affordability to the purchasing enterprise.

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