Modernising submarine structural design capabilities for next generation submarines

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Synopsis

Do semi-empirical equations written in FORTRAN have a place in submarine design in the age of digital twins, genetic algorithms and coupled multi-physics simulations?

Submarine programmes do not have the opportunity to build a prototype, due to the cost and time required to design and build a submarine the first boat manufactured is the first of class. As a consequence, submarine designs tend to be conservative and incremental in their development. The basic analytical design equations for UK submarine pressure hulls were developed in the 1960s, and coded into FORTRAN in the 1970s. These equations have been proven by model scale testing and physical trials and by continued operation of the current and previous classes of UK submarine.

Over the last six years QinetiQ have worked closely with the UK Ministry of Defence (MOD) to migrate these semi-empirical equations written in FORTRAN from obsolete HPUX based hardware to modern PC based systems with new graphical and command line user interfaces. These tools have been verified against the legacy code, updated to reflect the current UK structural design standards and fully documented. These updates have provided a modern, intuitive and supported user interface to the legacy equations, enabling their continued use. The new interfaces have also enabled the equations written in FORTRAN to be linked to modern tools such as Isight for process automation and optimisation. This enables a design of experiment (DoE) or optimisation studies with ten thousand iterations to be run within a week using a known, trusted and well understood toolset.

The migration and updates to these legacy tools have enabled them to be used in a way that would never have been considered when they were developed. The new approach enables a much wider exploration of the design space, and the ability to understand the sensitivity of the design to a given parameter. The capability has supported the development of a suite of automated Finite Element tools in Abaqus CAE Finite Element (FE) software, which automate and standardise the building and analysis of submarine pressure hull compartments. The ability to quickly and easily verify the FE analysis against the analytical tools for known cases has accelerated the development and confidence in the standardised FE process and by expanding the range of designs compared has started to identify the limitations of the analytical tools.

Coupling the analytical and FE tools together using Isight enables a potentially powerful parametric design tool, which can quickly run large numbers of low fidelity analytical solutions to identify potential solutions for further evaluation using linear and non-linear FE analysis which could form the basis for a digital twin of the submarine structure for use to support the platform through life.

Keywords: Submarine Structures, Analytical Tools, Pressure Hull Design, FEA, Optimisation

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Authors Biographies

Dr Richard Craven, holds a PhD from Imperial College London in Impact on Composite structures and has spent over 15 years working on the design analysis and failure of large structures. He is Principal engineer at QinetiQ where he leads engineer programmes and provides consultancy in the maritime composites and structures domain.

Dr David Tanner is a Chartered Engineer and has spent over 15 years working in mechanical structures engineering in academia (research and teaching), industry, consulting and latterly the UK Civil Service. He is now a Senior Specialist Fellow in Computational Structural Integrity Assessment.

Dr Derek Graham is a Technical Consultant for Submarine Structures and is a QinetiQ Fellow. He has spent the last 30 years at QinetiQ and its predecessor organisations, mostly refining the application of FE analysis to structural issues associated with the pressure hull and other structures.

1. Introduction

The current UK submarine design capability and the authors' QinetiQ Rosyth can trace their roots back to the Naval Construction Research Establishment (NRCE) based in St Leonards in Dunfermline, and fabrication and physical testing of model scale pressure hull compartments conducted in the Royal Naval Dockyard in Rosyth. The first full summary of the UK design of submarine hulls for static strength was written in an internal report of the NCRE by Bill Kendrick. A modified version of that report was later published openly as a book chapter by Kendrick (1970).

Kendrick later added an elasto-plastic overall collapse analysis and many others have contributed to development since, however, the basic design philosophy remains unchanged. These basic analytical and semi-empirical equations still underpin the submarine design capability today. There are a number of reasons for this, the designs produced have been shown to be efficient and reliable even against, modern numerical finite element methods of design. Without the opportunity of building full scale prototype designs, due to the time and cost required for production of a submarine, the relatively small numbers produced in each class and the safety of the platform of the upmost importance, submarine design is understandably conservative which explains the longevity of this design process.

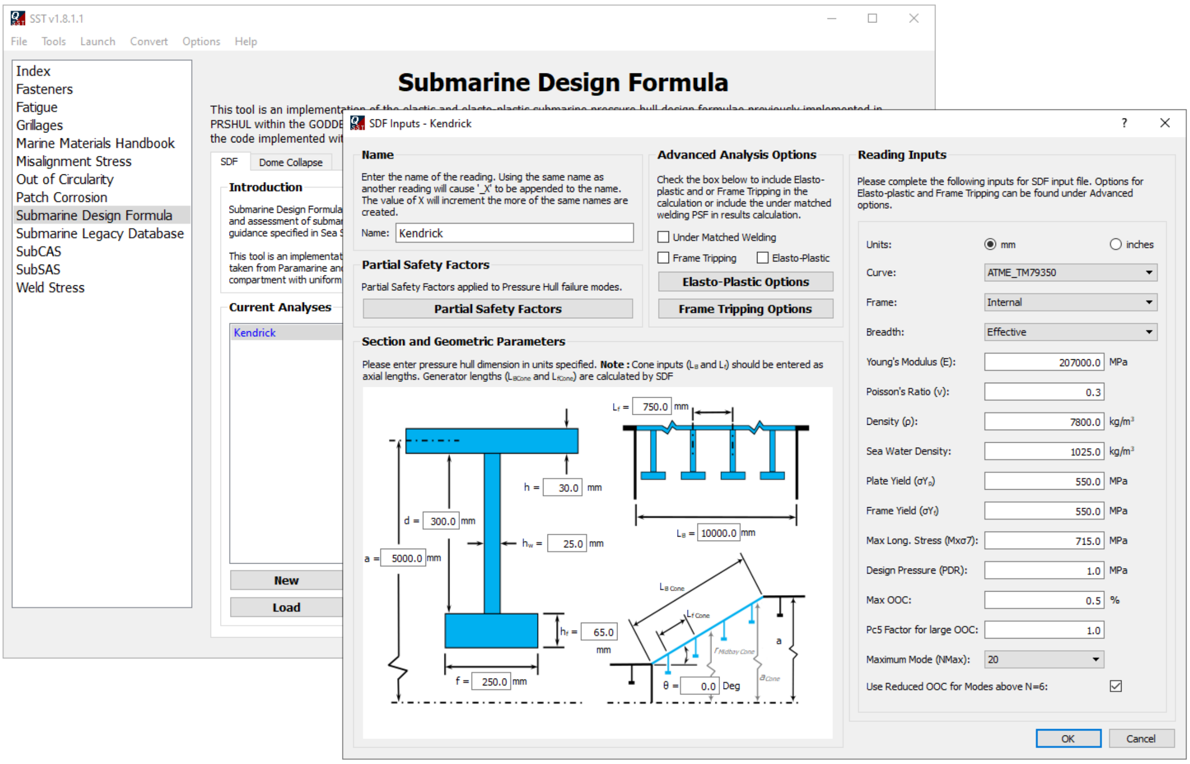
The equations developed governing pressure hull collapse were originally coded into discrete FORTRAN programmes in the early 1970s and run on main frame computers. These were combined into an integrated module called PRSHUL itself part of a ship and submarine design tool called GODDESS in the early 1980s which originally ran on bespoke hardware and was migrated onto Vax terminals and then HP-UX® machines in the late 1990s. In the early 2010s the UK MOD (Ministry of Defence) identified a need for replacement for the PRSHUL and various other legacy submarine structural analysis tools in a modern, accessible supported format on a Windows® based platform. As part of this ongoing initiative MOD and QinetiQ have been working together to gather legacy design tools together in a more modern, maintained and supported environment. This has resulted in the development of the Submarine Structural Toolkit (SST), which is used extensively within QinetiQ and the MOD and has now been rolled out to industry.

This paper will focus on the development, application and use of the SST plugin and the additional Finite Element Analysis (FEA) capabilities that have developed as part of the toolkit and the way that these tools are being used by the team today in order to answer the question. *Do semi-empirical equations written in FORTRAN have a place in submarine design in the age of digital twins, genetic algorithms and coupled multi-physics simulations?*

2. SST Development

SST has been developed over the last six years by QinetiQ in collaboration with the MOD. The software is Windows based with a Graphical User Interface (GUI) written in the python programming language, which interfaces with a range of closed form and semi empirical solvers, which can be categorised as Fast Running Engineering Models (FREMs), as opposed to FEA, or Computational Fluid Dynamics (CFD) type simulations. The solvers are a combination of python modules written to replace legacy spreadsheet or other obsolete toolsets, and legacy FORTRAN subroutines linked to directly from the python front end, such as PRSHUL. For the purposes of this paper the Submarine Design Formula (SDF) contained within the PRSHUL module will be used as a representative example of the tools contained within SST.

One of the key objectives of the SST software is to be quick, easy and intuitive to use, supported with clear and concise help and theory accessible from within the software. The purpose of this is to make the calculation process, fast, robust and repeatable, so the layout of the GUI and the inputs are designed to be consistent and intuitive across all of the tools. An example of the main screen and the inputs for a new model for the SDF tool can be seen in Figure 1.



Name

Enter the name of the reading. Using the same name as another reading will cause '_X' to be appended to the name. The value of X will increment the more of the same names are created.

Name: Kendrick

Partial Safety Factors

Partial Safety Factors applied to Pressure Hull failure modes.

Advanced Analysis Options

Check the box below to include Elasto-plastic and or Frame Tripping in the calculation or include the under matched welding PSF in results calculation.

☐ Under Matched Welding
☐ Frame Tripping ☐ Elasto-Plastic

Section and Geometric Parameters

Please enter pressure hull dimension in units specified. **Note :** Cone inputs (L_B and L_f) should be entered as axial lengths. Generator lengths (L_{BCone} and L_{fCone}) are calculated by SDF

h = 30.0 mm
d = 300.0 mm
h_w = 25.0 mm
a = 5000.0 mm
h_f = 65.0 mm
f = 250.0 mm
L_f = 750.0 mm
L_B = 10000.0 mm
θ = 0.0 Deg

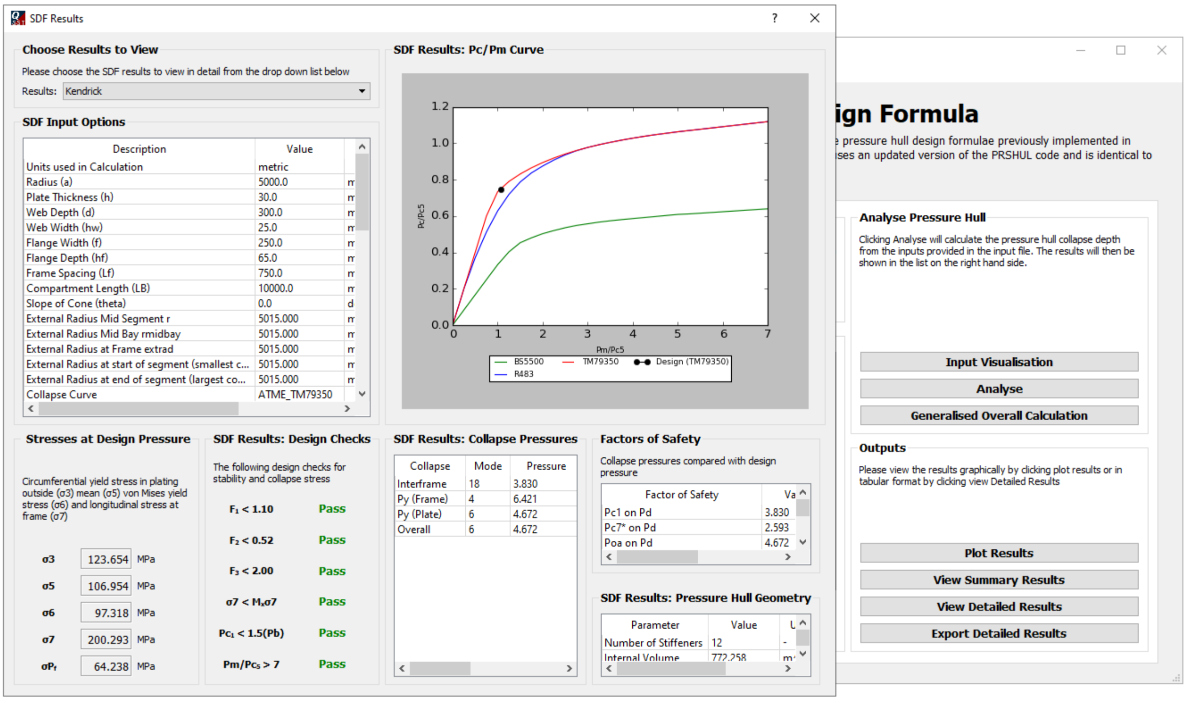
Reading Inputs

Please complete the following inputs for SDF input file. Options for Elasto-plastic and Frame Tripping can be found under Advanced options.

Units:	● mm ○ inches	
Curve:	ATME_TM79350	
Frame:	Internal	
Breadth:	Effective	
Young's Modulus (E):	207000.0	MPa
Poisson's Ratio (ν):	0.3	
Density (ρ):	7800.0	kg/m³
Sea Water Density:	1025.0	kg/m³
Plate Yield (σY_p)	550.0	MPa
Frame Yield (σY_f)	550.0	MPa
Max Long. Stress (Mxσ7):	715.0	MPa
Design Pressure (PDR):	1.0	MPa
Max OOC:	0.5	%
Pc5 Factor for large OOC:	1.0	
Maximum Mode (NMax):	20	
Use Reduced OOC for Modes above N=6:	☑	

Figure 1: SST graphical user interface for submarine design formula tool

The PRSHUL module takes seconds to run and multiple models can be run sequentially in a batch allowing the user to run multiple compartments or variations on a single geometry quickly. The results can then be displayed for the user, with a summary of the key results presented Figure 2. The user can access the summary or detailed results and plots through the GUI if required. All results and plots can also be exported for inclusion in reports or presentations or simply to keep a record of the calculations run.



Choose Results to View

Please choose the SDF results to view in detail from the drop down list below

Results: Kendrick

SDF Input Options

Description	Value	
Units used in Calculation	metric	
Radius (a)	5000.0	m
Plate Thickness (h)	30.0	m
Web Depth (d)	300.0	m
Web Width (hw)	25.0	m
Flange Width (f)	250.0	m
Flange Depth (hf)	65.0	m
Frame Spacing (Lf)	750.0	m
Compartment Length (LB)	10000.0	m
Slope of Cone (theta)	0.0	d
External Radius Mid Segment r	5015.000	m
External Radius Mid Bay rmidbay	5015.000	m
External Radius at Frame extrad	5015.000	m
External Radius at start of segment (smallest c...	5015.000	m
External Radius at end of segment (largest co...	5015.000	m
Collapse Curve	ATME_TM79350	

Stresses at Design Pressure

Circumferential yield stress in plating outside (σ3) mean (σ5) von Mises yield stress (σ6) and longitudinal stress at frame (σ7)

σ3	123.654	MPa
σ5	106.954	MPa
σ6	97.318	MPa
σ7	200.293	MPa
σP_f	64.238	MPa

SDF Results: Design Checks

The following design checks for stability and collapse stress

$F_1 < 1.10$	Pass
$F_2 < 0.52$	Pass
$F_3 < 2.00$	Pass
$\sigma 7 < M_x\sigma 7$	Pass
$Pc_1 < 1.5(Pb)$	Pass
$Pm/Pc_5 > 7$	Pass

SDF Results: Collapse Pressures

Collapse	Mode	Pressure
Interframe	18	3.830
Py (Frame)	4	6.421
Py (Plate)	6	4.672
Overall	6	4.672

Factors of Safety

Collapse pressures compared with design pressure

Factor of Safety	Va
Pc1 on Pd	3.830
Pc7* on Pd	2.593
Poa on Pd	4.672

SDF Results: Pressure Hull Geometry

Parameter	Value	U
Number of Stiffeners	12	-
Internal Volume	772.258	m

pressure hull design formulae previously implemented in
ses an updated version of the PRSHUL code and is identical to

Analyse Pressure Hull

Clicking Analyse will calculate the pressure hull collapse depth from the inputs provided in the input file. The results will then be shown in the list on the right hand side.

Outputs

Please view the results graphically by clicking plot results or in tabular format by clicking view Detailed Results

Figure 2: SST graphical user interface for submarine design formula summary results

A command line interface version of the SST software has also been created for a subset of the tools within SST including SDF, this enables the user to run the tool from the command line, without the graphical user interface, by providing the same inputs in a text file format. These inputs are then processed through the same error checking, solution and reporting functionality used by the GUI version of SST to ensure consistency between both tools. Whilst this command line interface might seem backward in an age of smart phones and touch screen interfaces. The potential of the command line interface is the ability to include the SST tools within automated workflows, batch process i.e. optimisation or design of experiment or robustness studies that can be driven by a simple spreadsheet or a more advanced optimisation tool such as Isight®, or modeFrontier®.

The SST tools have been extensively tested and verified using code to code comparison for a range of submarine compartment models, covering a range of lengths, diameters, stiffener configurations and failure modes against the original PRSHUL implementation within GODDESS and other independent codes which perform the same or similar analysis of the pressure hull collapse problem. This verification has generally shown excellent correlation with the results across the range of models tested, with the exceptions of parts of the code that have been deliberately updated to better represent the current MOD design guidance.

3. Development of finite element analysis tools

Whilst the SDF tools are quick and reliable and are now more easily and widely accessible to users within the SST software and produce efficient designs and have an excellent pedigree and validation, the analytical tools have limitations. The SDF tool assumes a uniform axisymmetric structure and has limited ability to include effects of shape imperfections, or irregularity within the structure. Similarly each of the potentially interacting, failure modes are considered in isolation. Whilst the current design rules ensure development of designs that fail in a single mode and partial safety factors ensure separation of the modes. This approach could miss potentially optimal designs that have greater performance albeit with a more complex or mix mode failure. Therefore despite being slower, FEA is likely to provide a more accurate answer for the actual collapse pressure for a given design due to the higher fidelity of the model, the ability to capture more detail and to model the interaction between failure modes and potential to explore the design space outside of the current design rules.

QinetiQ has been collaborating with the MOD over the last 15 years to develop a process and a deep technical understanding of the use of the finite element method to the collapse of pressure hulls, and has developed a methodology for the modelling and analysis of the collapse of pressure hull structures as summarised by Graham in (2007 and 2014). This methodology includes an understanding of the importance of the relative components of the pressure hull in the collapse of the overall structure, the importance of including thickness, positional and material property variations as well as manufacturing induced defects such as residual stresses and shape imperfections.

Validation of this modelling methodology was carried out using legacy data from many of the models tested at Rosyth and used to develop the UK design rules see Graham (2007). These models were relatively large scale and were fabricated using similar processes to those used at full scale and therefore included fabrication residual stresses and shape imperfections representative of those present in real submarine pressure hulls. FEA models that were true representations of the ‘as-built’ structures, including cold bend residual stresses, were generated. The analyses showed a consistent trend in that the FEA over-predicted the experimental collapse pressure by an average of about 6 %, which is consistent with predictions reported by other research programs, e.g. Mackay (2011).

More recent large-scale model tests have used modern laser scanning and ultrasonic techniques to measure shape and plate thicknesses in much more detail than had been previously possible. Which allowed precise FE models of the as-built structures to be created. They were also extensively instrumented which allowed detailed comparisons of the non-linear structural response to be carried out.

The ratio of predicted to experimental collapse pressure for seven models from two test programmes, three Canadian (Swanek 2013) and four UK HCT (Hydrostatic Collapse Trial) (Brooke 2014) cylinders are summarised in Table 1. Despite the two cases where FEA under-predicted the experimental collapse pressure in this small sample, the general trend is for FEA to over-predict the experimental value. This is supported by a Canadian review by Mackay (2011). With sufficient detail of shape, scantlings and residual stresses experience suggests that we should expect FEA to be within +2 % to +9 % of the experimental collapse pressure, bearing in mind this is based on a relatively small sample size.

Table 1: Accuracy of 'as-built' FEA predictions.

Pressure Hull Model	**FE / Experiment**
Canadian cylinder A	1.028
Canadian cylinder B	1.068
Canadian cylinder C	0.93
UK HCT Cylinder 1	0.96
UK HCT Cylinder 2	1.070
UK HCT Cylinder 3	1.020
Confirmation model	1.025

Whilst it is practical to model the as built laser scan structure to capture thickness and shape imperfection of a production item or a test model. This is not a practical approach from a design perspective, so some assumptions have to be made. A programme of work was undertaken to generate a representative pseudo as-built shape based on idealised components, presented in (Graham 2014). These consisted of overall Out-Of-Circularity (OOC), axisymmetric inward deformation between frames (Hungry Horse), and an interframe buckling pattern in a critical mode for the compartment modelled. Examples of these three shape imperfections are shown in Figure 3. These were combined to form an overall shape of the form Figure 4, the amplitude of the deformation has been scaled in order to visualise the modes discussed.

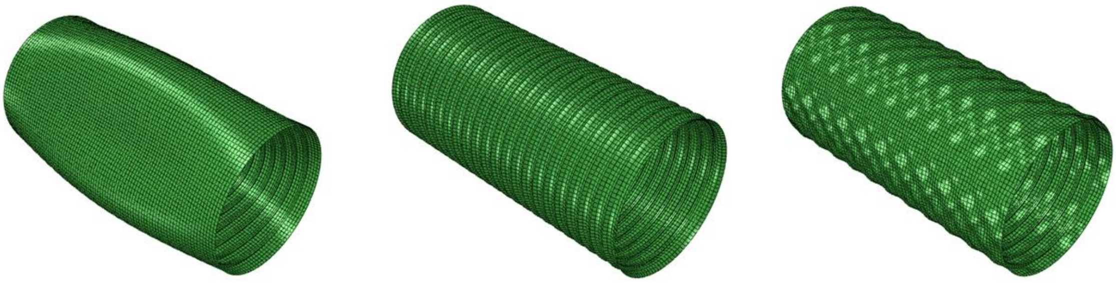


Figure 3: Idealised shape imperfection components (Overall, Hungry-Horse and Interframe buckling)

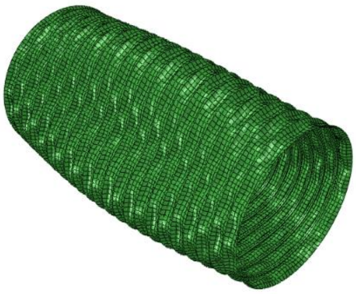
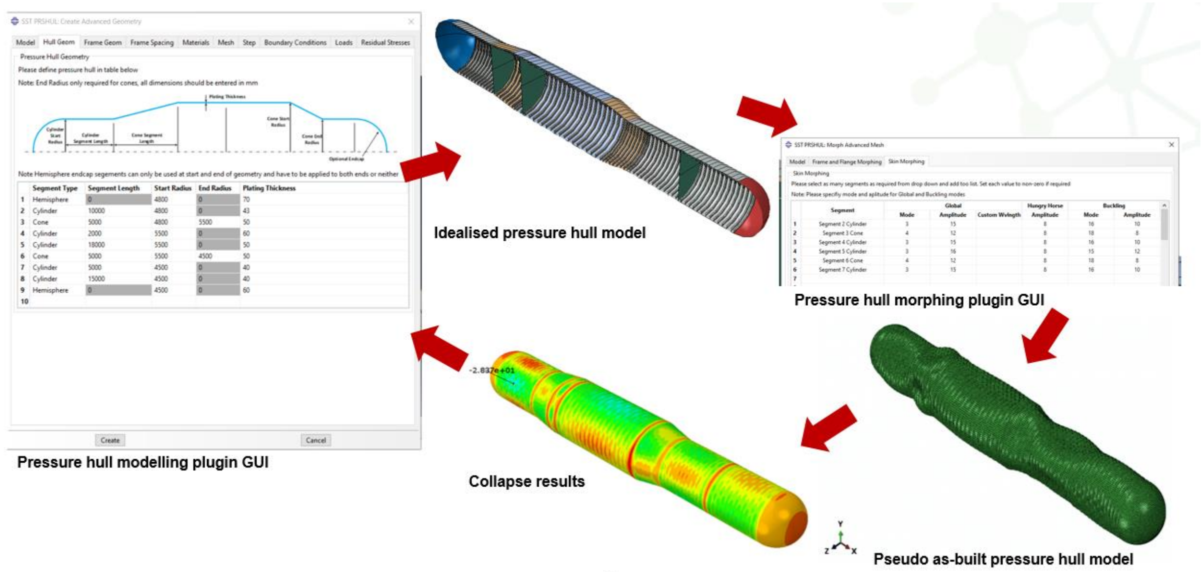


Figure 4: Pseudo as-built shape

This standardised process for the FEA of pressure hull collapse has been developed into a suite of analysis tools that automate and encapsulate the best process analysis for 2D and 3D pressure hull and collapse models. This suite of plugins to Simulia Abaqus® CAE is an extension to the SST capability into the FEA domain. Although the capability could be implemented in any commercial Non-linear FEA solver.

The same design philosophy has been applied to the FEA tools as used for the analytical SST software. The interfaces have been developed to be intuitive and easy to use allowing the user to quickly, repeatably and robustly build models of a single frame up to an entire pressure hull. The tools allow the user to load and save inputs and load in tables of scantlings from a spreadsheet or other source. As well as containing all the geometric features typically found on a pressure hull: Internal and external stiffeners, bulkheads, cylinders, conic sections and end closures. The user can apply the idealised shape imperfection described above, and solve for linear perturbation, buckling or non-linear collapse analysis. Post-processing the models to extract the results is also automated within the tools.

An idealised representation of a workflow is presented below, this process would typically take two hours including solution time on a standard Windows® workstation laptop, Figure 5.



SST PRSHUL: Create Advanced Geometry

Pressure Hull Geometry

Please define pressure hull in table below

Note: End Radius only required for cones, all dimensions should be entered in mm

Note Hemisphere endcap segements can only be used at start and end of geometry and have to be applied to both ends or neither

	Segment Type	Segment Length	Start Radius	End Radius	Plating Thickness
1	Hemisphere	0	4800	0	70
2	Cylinder	10000	4800	0	43
3	Cone	5000	4800	5500	50
4	Cylinder	2000	5500	0	60
5	Cylinder	18000	5500	0	50
6	Cone	5000	5500	4500	50
7	Cylinder	5000	4500	0	40
8	Cylinder	15000	4500	0	40
9	Hemisphere	0	4500	0	60
10					

Pressure hull modelling plugin GUI

Idealised pressure hull model

SST PRSHUL: Morph Advanced Mesh

Skin Morphing

Please select as many segments as required from drop down and add too list. Set each value to non-zero if required

Note: Please specify mode and aplitude for Global and Buckling modes

	Segment	Global			Hungry Horse	Buckling	
		Mode	Amplitude	Custom Wvlngth	Amplitude	Mode	Amplitude
1	Segment 2 Cylinder	3	15		8	16	10
2	Segment 3 Cone	4	12		8	18	8
3	Segment 4 Cylinder	3	15		8	16	10
4	Segment 5 Cylinder	3	16		8	15	12
5	Segment 6 Cone	4	12		8	18	8
6	Segment 7 Cylinder	3	15		8	16	10
7							

Pressure hull morphing plugin GUI

Collapse results

Pseudo as-built pressure hull model

Figure 5: FE Pressure Hull Analysis workflow, for geometry creation, application of shape imperfection and non-linear collapse analysis (implemented in Simulia Abaqus CAE)

As with the analytical tools in SST the FEA based tools also have a GUI and command line interface enabling the FEA tools to be used in the same automated workflows, optimisation loops and design of experiment studies as the analytical tools.

4. Verification of the newly developed toolsets

Due to the relatively limited pool of validation cases for FEA tools described in the previous section, verification of the FEA tools within SST and the design process encapsulated within the tools, a robust verification process was an important part of the development. The verification activities have been discussed in more detail in Graham (2021). However, in summary the submarine design formula equations within the PRSHUL FORTRAN module of SST were used to compare with the FEA results for a range of compartment lengths, diameters, frame sizes and spacings. The comparison of the results is shown in Figure 6.

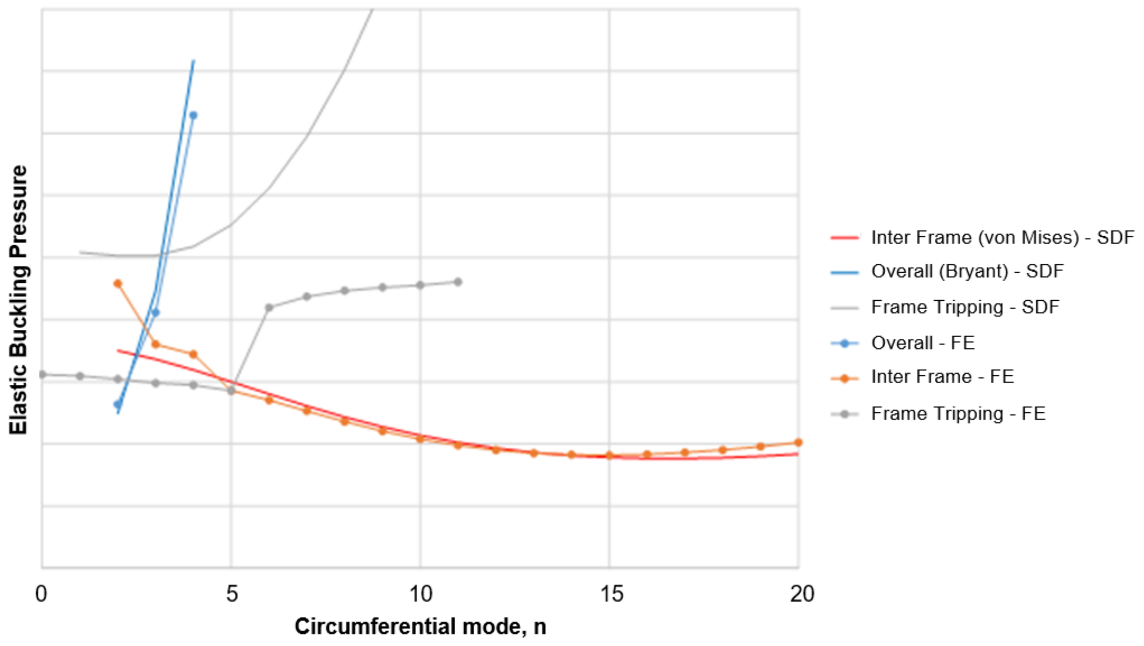


Figure 6: Comparison of FEA and SDF predictions for Elastic Buckling Pressures

Comparison of overall and interframe modes in general give good agreement between the analytical equations implemented within SDF and the numerical predictions of the FEA tools. Albeit, there is a significant difference in the predicted frame tripping failure mode. Initially the FEA appeared to not be capturing the behaviour captured by the analytical method. However, on further investigation of the analytical method, an early application of energy methods, it was identified that the shape function used for the frame web, was equivalent to a single higher order element on the web. When the fidelity of the mesh in the FEA model was reduced to a single higher order element for the web a much closer correlation was achieved between the Frame Tripping implementation in PRSHUL and the FEA model. Mesh convergence studies performed on the FEA model showed a single higher order element on the web did not give a converged solution. This suggests the assumed shape function in the analytical frame tripping solution is unconservative and FEA provides a better estimate of frame tripping pressure than the SDF equations.

The ability to quickly compare a range of pressure hull geometries between the FEA and SDF tools is providing verification of the FEA tools but also enabling assessment of the SDF tools outside of the range of model scale tests used for validation of the tools. This verification exercise quickly identified where the analytical equations deviate from the FEA results, typically outside the bounds of the physical testing, or as in the case of the frame tripping analysis where the tools are significantly less accurate than the FEA approach.

5. Unlocking the potential of legacy FORTRAN applications

The ability to run the legacy PRSHUL FORTRAN module within the SST software on a Windows® platform immediately increases the accessibility to users compared with obsolete HP-UX® hardware. The ability to run SST from the command prompt immediately increases the capability and flexibility for running multiple iterations of the SDF calculations quickly and repeatedly. A MS Excel® spreadsheet has been developed which allows users to perform full factorial design of experiment analysis for many combinations of input parameters within SDF tool, this can enable the user to generate tables of results of a thousand or more runs, within a few hours on a laptop. Integrating the same command line version of SST into a basic Isight® workflow, with some simple calculators and constraints, it is possible to run and post process 30,000 – 40,000 SDF calculations and draw meaningful conclusions. This number of calculations would have been inconceivable even ten years ago, when a similar study might have run and processed 30 – 40 individual analysis over the course of several weeks.

Similarly, when SST is used in an optimisation loop, non-intuitive designs can emerge that achieve modest weight savings, the current submarine design formulae drive weight efficient designs, whist achieving an increase in collapse pressure, and significant reductions in peak stresses. Again these optimisation studies have iterated over thousands or tens of thousands of SDF calculations which would simply not be feasible manually and are identifying solutions which are unlikely to have been identified using a classic incremental manual design approach. This potential is not limited to the analytical tools within SST, exactly the same approach can be applied to the use of the FEA tools within SST. These can be run through optimisation and design of experiment loops and can achieve more accurate results and explore the design space outside of the limitations of the SDF calculations.

The FORTRAN based SDF calculations still have their place, these tools run 100 – 200 times faster than an equivalent FEA calculation, they do not require license tokens from a finite pool of paid for tokens and are far less computationally intensive to run. In the authors opinion it is not a case of choosing one tool over the other, rather it is expected that these tools will be used to complement each other. The SDF calculations can be used to widely explore the design space and identify potential optimums for a given requirement set then the FEA analysis can be used to confirm the prediction and refine the design based on the output of the SDF optimisation. An idealised workflow to represent this concept, which also suggests the potential for considering other aspects, such as fatigue performance, cost and manufacturability considerations as part of the overall pressure hull design workflow Figure 7.

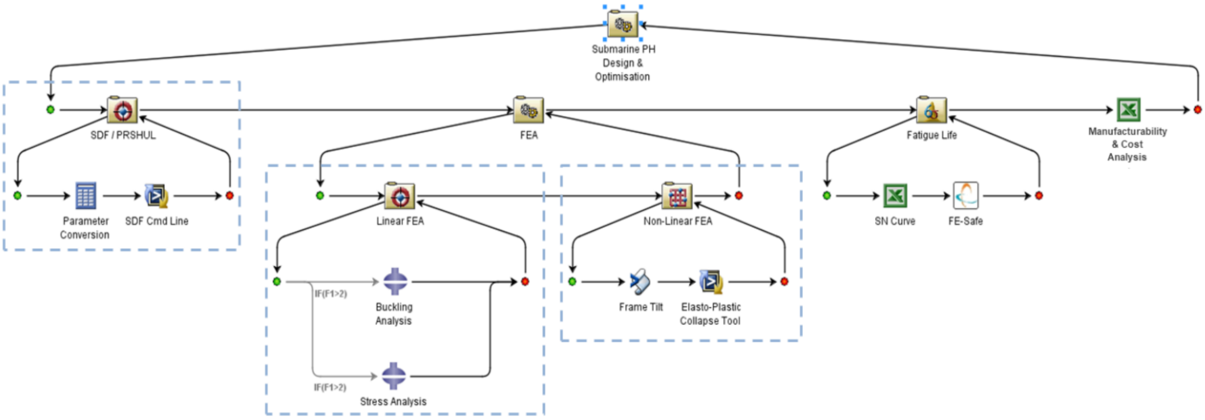


Figure 7: Conceptual pressure hull design workflow, including multiple aspects of the design process.

Other potential applications for the SDF analytical tools include using sensitivity and robustness analysis to determine the sensitivity of designs to a tolerance, or non-conformity of the design, to build up response surfaces and sensitivity studies, which could help to understand the sensitivity to a given parameter, as well as the effects of combinations of sensitivities, this could be used to support a review of manufacturing tolerances, which may demonstrate that certain current tolerances are overly prescriptive and could be relaxed, which might reduce manufacturing cost and or process time during build. Such analysis could also identify areas where tolerances should actually be tightened. Similarly using a combination of the SDF analytical and numerical FEA tools idealised representations of common manufacturing non-conformities can be assessed as single non-conformities and as different combinations of non-conformities, in order to determine the effect on the pressure hull of interactions between the non-conformities. Previously this type of analysis has tended to be reactive in response to a specific issue, with the new capabilities this can become routine, predictive analysis, improving the understanding of the impact of manufacturing imperfections on the pressure hull collapse pressure.

6. Summary: Why is FORTRAN still relevant?

In summary, QinetiQ and the MOD have collaborated to create a suite of submarine structural analysis tools, with graphical and command line interfaces, this suite of tools includes a mixture of legacy FORTRAN semi-empirical equations such as the submarine design formula, and modern numerical non-linear Finite Element Methods for analysing the collapse of pressure hull structures. Although any novel designs outside of the current design space, would need their capability confirming through physical testing, before any such design would be considered for use on a manned platform.

Combining these tools with process automation and optimisation tools has driven a step change in the design and analysis capability, both in the sheer number of analyses that can be undertaken and in the potential applications to which the toolset can be applied for the design of submarine pressure hulls. This will enable the use of FEA much earlier in the design space.

To answer the question, posed in the abstract. *Do semi-empirical equations written in FORTRAN have a place in submarine design in the age of digital twins, genetic algorithms and coupled multi-physics simulations?* In the authors opinion yes, semi-empirical equations written in FORTRAN such as the SDF PRSHUL module absolutely have a place in submarine pressure hull design today. Whilst some aspects of the tools are now shown to be unconservative such as the frame tripping analysis the core functionality still produces weight efficient, safe designs, quickly and repeatedly, with extensive verification and validation and a pedigree of proven designs, which give confidence in an understandably conservative industry. Due to the newly developed interfaces to the equations written in FORTRAN, the potential for running large numbers of analysis, tens or hundreds of thousands, very quickly to support, optimisation, design of experiments, robustness and sensitivity analysis opens up new potential uses and understanding which can be derived from the tools as well as the potential for improved pressure hull designs, as a result of non-intuitive optimal solutions.

Similarly, as machine learning, artificial intelligence and digital twin capabilities progress then in future the same SDF tools could be used to generate the large training data sets to support, to train and develop these capabilities, and there are probably other applications where the legacy FORTRAN codes will still be equally applicable for future simulation capabilities.

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