Design Space Navigator
For
Steel Beam-Stiffened Plate Structures

Final Report

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Design Space Navigator
For
Steel Beam-Stiffened Plate Structures Users Manual

Abstract

This report describes the creation, theory, and use of custom software to speed up the evaluation of alternative designs aimed at meeting strength and weight goals for beam-stiffened plate structures used in Naval shipbuilding. The project has been funded by the National Shipbuilding Research Program (NSRP), as a "Panel Project" supported by the NSRP Ship Design and Material Technology Panel. Assumptions and general methodology are described, and instructions for use are included. A total of 13 input values are entered, which include the design allowables and criteria of American Bureau of Shipping Naval Vessel Rules (ABS NVR) and American Institute of Steel Construction (AISC) as well as other considerations such as material type, frame spacing, deflection criteria, etc. Once these values have been established, the program takes approximately five seconds to iterate several alternative designs. Designs that meet all the input criteria are saved; all others are rejected. The program outputs the acceptable designs into a spreadsheet. Thirty-two output values are provided for each design. Output data includes all of the sectional properties needed for evaluation including section modulus, moment of inertia, structure weight per square foot, as well as "utilization factors" or what percentage of allowable stress is borne by each element in the design. At this writing, a beta version has been evaluated by two US shipyards, with good reviews.

Disclaimer

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Introduction and Concept Description

Nearly all ship classes, and especially combatants, make use of beam-stiffened plate structures, utilizing a significant amount of Hot-Rolled (HR) structural shapes for stiffening shell, deck and bulkhead plating, as well as other applications. Designers are faced with the challenge that the typical deck, bulkhead, or shell structure is made of plate combined with HR shapes. While there is data available for the properties of the shapes [4 and many other sources], the designer must compute the combined properties of the structure. To meet this need, the Society of Naval Architects and Marine Engineers (SNAME) published in 1961, a manual of combined properties of beam and plate [5], which listed various plate thicknesses and stiffeners in combination. This manual and its subsequent revisions have served to aid designers for a half-century. A major limitation is that the designs only consider the standard offerings of steel mills.
As the need grows for better performance and control of weight and KG, and as the economic forces drive steel producers to make fewer profiles, the acquisition of structurally efficient HR shapes becomes more difficult for the designer. An alternative that is being increasingly evaluated is the use of custom-fabricated sections. The comparison between custom-fabricated shapes and HR profiles below shows that HR profiles have several disadvantages:

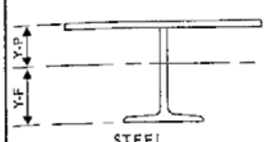
- **Design** Designed primarily for buildings, the structural properties of HR profiles seldom match those needed for ships; fabricated shapes can provide weight savings of 10-30%.
- **Type of Steel** HR shapes used in Shipbuilding are only available using ABS AH-36, Grade A, and ASTM A36 steels; thus, heavier shapes are needed - higher strength steels could provide as much as 50% weight savings.
- **Overweight** As received HR shapes are typically 5-7% “overweight” due to hot-rolling equipment tolerances; this can increase the weight of a DDG-51 by over 50 tons with negative impact on vessel weight and vertical center of gravity (KG).
- **Poor Dimensions** HR shapes are made to tolerances that are *twice* those of naval vessel requirements; causing delays in fitting and frequent rework; fabricated shapes can be made more accurate, with significant savings in assembly costs.
- **Non-value added costs** DDG-51 material catalog requires more than 210 different HR line items to supply the needed I-beams and Tees (more than 90% using ABS AH-36), each with min/max levels that must be checked and maintained. In contrast, all of the custom-fabricated profiles can be made from just 12 thicknesses of plate, all of which are already in inventory, providing significant savings in shipyard overhead costs.

Fabricated shapes have replaced many of the HR beams in both the CVN-78 and DDG-1000 vessels. Indeed, achieving weight and KG would have been difficult to meet without the use of custom-designed, weight efficient, fabricated shapes. In the CVN-78, savings on the order of 1500 tons (more than 400 tons just in the shapes) were achieved by using a higher-strength, (65 vs. 51 ksi) steel [1]. The superior accuracy has been well-received by the shipyard, with requests from the deck plate to continue their use. For these programs, significant effort was expended to accomplish these new, non-traditional designs.

Many other ship design projects (especially modification and repair) might not have the resources to perform such detailed analysis. For this reason, an NSRP "Panel Project" was awarded for the purpose of creating an integrated tool to allow fast and effective conversion of existing designs, and efficient evaluation for new designs. Such a tool would build on and make use of existing data and generate new information as needed. The completed package would be available to all shipyards in accordance with the IP rules of the NSRP.

Applied Thermal Sciences (ATS), of Sanford Maine, has developed this tool, called the "Design Space Navigator," in conjunction with Marinette Marine (MM), Huntington-Ingalls Industries (HII-Ingalls) and Concurrent Technologies Corporation. The Navigator consists of software to perform a series of calculations that generate the output of a range of profile dimensions and properties as well as the weight per square foot of the beam-stiffened structure. The output is loaded into a spreadsheet so that the various options can be compared and an optimal solution selected. One feature of the tool is a "utilization factor", which reports how well the design makes use of the properties of the beam. This tells the designer if a structure is "over-designed" or, alternatively, how much "reserve strength" is contained in the design.

The Navigator allows the comparison of a wide variety of test cases in minutes by performing the same detailed calculations that designers do with hand calculators; all based on existing allowable stresses, expected loads, safety factors, and design-governing criteria such as Naval Vessel Rules and American Institute of Steel Construction requirements [2-4]. It can replace exhaustive volumes of properties of beam/plate structures [5] that have been used but seldom updated to include the latest materials and profiles now available to designers. Typical data from the reference 5 is shown in Figure 1.



PROPERTIES OF
COMBINED BEAM AND PLATE
I-T AND T

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5.1# PLATE WEIGHT

NOMINAL SIZE	WEIGHT PER FOOT	SECTION MODULUS		I	r	YF	YP	BEAM DIMENSIONS				
		LESSER	GREATER					AREA	DEPTH	FLANGE WIDTH	FLANGE THICK	SHEAR AREA
IN. x IN. x LBS./FT.	LBS.	IN.³	IN.³	IN.⁴	IN.	IN.	IN.	IN.²	IN.	IN.	IN.	IN.²
18 x 11 3/4 x 105 I-T	71.22	70.6	161.4	905.8	6.43	5.6	12.8	20.95	18.32	11.79	0.911	10.14
96 I-T	65.10	65.2	148.0	827.6	6.42	5.6	12.7	19.15	18.16	11.75	0.831	9.29
18 x 8 3/4 x 85 I-T	60.34	66.1	128.7	805.3	6.56	6.3	12.2	17.75	18.32	8.84	0.911	9.63
77 I-T	54.46	60.4	117.4	728.9	6.56	6.2	12.1	16.02	18.16	8.79	0.831	8.62
70 I-T	49.48	55.6	106.9	663.0	6.54	6.2	11.9	14.55	18.00	8.75	0.751	7.88
64 I-T	45.19	51.7	98.3	609.4	6.54	6.2	11.8	13.29	17.86	8.71	0.686	7.20

Figure 1 Typical Catalog data

This beta version has undergone preliminary evaluation at both MM and HII. This paper outlines the considerations used to develop the tool, describes its operation, and details the data flow and equations used to make the calculations that generate the output.

Using the Design Space Navigator

Some Basic Information The Navigator is intended to be used by personnel competent in basic structural engineering design. The basic hardware platform needed includes a PC with Microsoft Office Excel™ version 2007.

All of the input and output data terms, including nomenclature and description, are listed in Tables I and II immediately following this section. In addition, when appropriate, the standards or criteria from which they are drawn are identified.

The current version of the Navigator has been set up to follow the requirements of AISC and ABS NVR. When there is a conflict between these two documents, the more conservative requirement is used for calculation. Furthermore, the present version mirrors the "Manual of Combined Properties" [5] in that only one material is evaluated for all three elements (plate, stiffener web, and stiffener flange) of the structure. Subsequent versions of the Navigator will allow the user to select different materials for each of these elements.

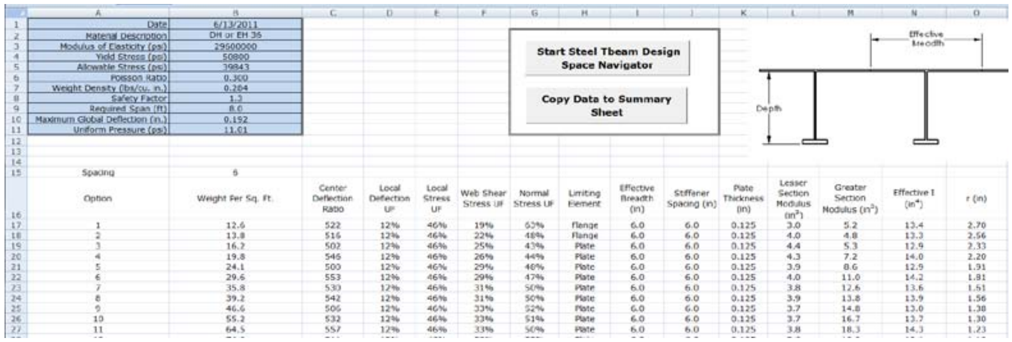
Furthermore, the current version of the Navigator will only evaluate scenarios in which the loads are applied normal to the structure. The addition of in-plane loading conditions was beyond the scope of the original project, and will be considered for later versions.

The program requires 13 input items and generates 32 output data items for each solution of the design task. All of these are described in detail in tables 1 and 2 at the end of this section. The program generates 240 solutions: there are fifteen acceptable designs for each of sixteen longitudinal spacings from 6- to 96-inches in 6-inch increments.

Of the 13 input items, four are explicit requirements of AISC and NVR; these cannot be changed by the user. The other nine items are either entered by the user or are linked to a user selection. For instance, once a material (e.g. DH-36) has been selected, the values of density, yield strength, allowable stress, and other necessary properties for the selected material are pulled from a table and used throughout the computational cycle. At present, all of the structural steel alloys in the NVR are contained in the selection menu.

Operation of the Navigator

The user first sees the startup screen, as shown in Figure 2.



Date	6/13/2011
Material Description	DH or EH 36
Modulus of Elasticity (psi)	29600000
Yield Stress (psi)	50800
Allowable Stress (psi)	39843
Poisson Ratio	0.300
Weight Density (lbs/cu. in.)	0.204
Safety Factor	1.3
Required Span (ft)	8.0
Maximum Global Deflection (in.)	0.192
Uniform Pressure (psi)	11.01

Spacing 6

Option	Weight Per Sq. Ft.	Center Deflection Ratio	Local Deflection UF	Local Stress UF	Web Shear Stress UF	Normal Stress UF	Limiting Element	Effective Breadth (in)	Stiffener Spacing (in)	Plate Thickness (in)	Lesser Section Modulus (in^3)	Greater Section Modulus (in^3)	Effective I (in^4)	r (in)
1	12.6	522	12%	46%	19%	63%	Flange	6.0	6.0	0.125	3.0	5.2	13.4	2.70
2	13.8	516	12%	46%	22%	48%	Flange	6.0	6.0	0.125	4.0	4.8	13.3	2.56
3	16.2	502	12%	46%	25%	43%	Plate	6.0	6.0	0.125	4.4	5.3	12.9	2.33
4	19.8	546	12%	46%	26%	44%	Plate	6.0	6.0	0.125	4.3	7.2	14.0	2.20
5	24.1	500	12%	46%	29%	40%	Plate	6.0	6.0	0.125	3.9	8.6	12.9	1.91
6	29.6	553	12%	46%	29%	47%	Plate	6.0	6.0	0.125	4.0	11.0	14.2	1.81
7	35.8	530	12%	46%	31%	50%	Plate	6.0	6.0	0.125	3.8	12.6	13.6	1.61
8	39.2	542	12%	46%	31%	50%	Plate	6.0	6.0	0.125	3.9	13.8	13.9	1.56
9	46.6	506	12%	46%	33%	52%	Plate	6.0	6.0	0.125	3.7	14.8	13.0	1.38
10	55.2	532	12%	46%	33%	51%	Plate	6.0	6.0	0.125	3.7	16.7	13.7	1.30
11	64.5	557	12%	46%	33%	50%	Plate	6.0	6.0	0.125	3.8	18.3	14.3	1.23

Figure 2 Start-up Screen

The blue box on the left shows data entered in the prior use of the tool. The graphic on the right shows general descriptors of the structure. The center dialog box offers two "radio buttons"; the top one for starting the tool and the lower one for copying the data generated to a summary Excel™ spreadsheet. The data shown in the lower part of the screen is the output of the last analysis performed by the Navigator. Also, at the bottom of the display, there are three tabs (worksheets in Excel™ parlance). The "Calculation" tab is the environment in which input data is entered and output information is placed. The summary tab is a location into which the output data may be transferred. This provides a more convenient environment for navigation through the output data and performing any of the many data-reduction and sorting functions offered by Excel™. The third tab ("Weight Summary Chart") is a graphic showing the weight per square foot of the various stiffener spacing and TBeam options. Similar to the spreadsheet data seen on the Calculation tab when starting the Navigator, the data shown on Weight Summary tab is the output of the last calculation, and is replaced with new data when the calculation is complete.

Once the "Start" button has been activated, a "Load Input" dialog box appears, with seven items that offer various input options (Figure 3). Uniform pressure (normal loading), Span ("frame spacing") and Local Deflection Criteria are entered as numerical values by the user. Global Deflection Criteria are selected from a drop-down menu. The minimum plating thickness criterion is selected by choosing one of three Location/Loading Scenario cases, all of which are specific NVR requirements. The user has the option to proceed or quit. Pressing the quit button returns the user to the original input screen.

To calculate the local phenomena, the plating between the stiffeners is treated as an infinite plate in cylindrical bending with simple edges. Once the local (plating) criteria have been satisfied, the T-Beam elements are iterated to provide solutions that satisfy the global design criteria, using the concept of effective breadth. The global structure is modeled assuming a simply supported beam with a uniform load.

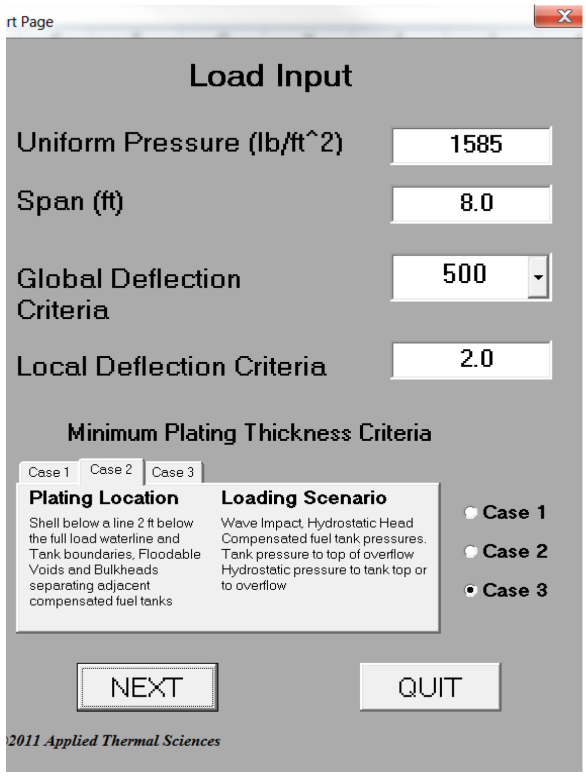


Figure 3 Load Input Dialog Box

When the load input information has been entered, and the "Next" button activated, the "Material Selection" dialog box opens. Figure 4 offers a selection of alloys, with the options to select an alloy, go back to the previous screen, or quit.

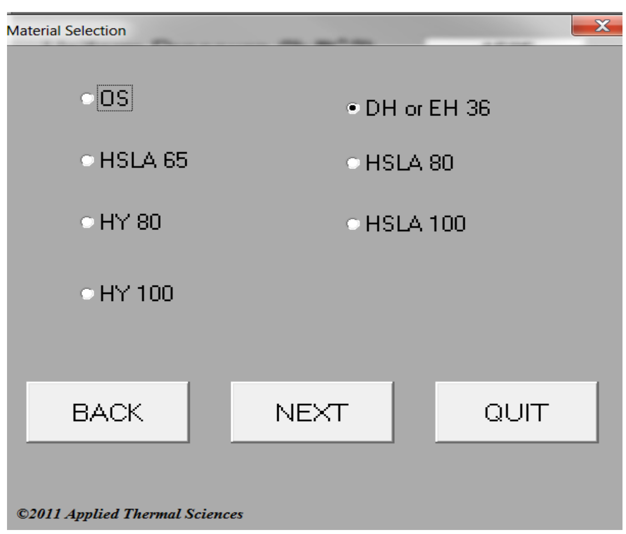


Figure 4 Material Selection Dialog Box

The alloys listed are the steel alloys allowed in the NVR. As mentioned earlier, the design will proceed on the assumption that the entire structure, plate and stiffener, are made of the same material. This "homogeneous" approach mirrors that taken by tables of properties such as reference [5] and other design handbooks. Recognizing that more and more, ship designs are taking advantage of combinations of alloys and strengths. Future versions of this software will explore the opportunity to use different materials for plate and shapes as well as a further improvement, the use of different materials for the deck, bulkhead, or shell plating, with stiffeners also made of different materials, such as lower strength webs and higher-strength flanges.

Once the alloy has been selected and the "Next" button activated, a summary dialogue box appears ("Calculate TBeams" – Figure 5). This box lists all the salient information entered to date, either by the user, or by implication, those values that are required by the NVR or AISC for the materials, loading, and load case selected. As before, the user has the option to go back to make changes, proceed, or quit. Activating the "GO" options starts the computational phase.

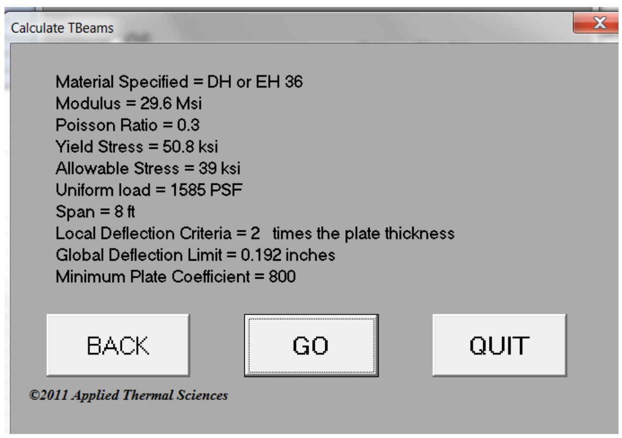


Figure 5 Calculate TBeams

Once the "GO" button is activated, the screen goes blank while the computation process proceeds. When the iteration cycle is finished, the screen reappears with the results. As noted earlier, more calculations are made during computation than those shown in the output. All potential solutions that do not meet the input criteria are rejected by the program, and only those meeting the criteria are listed in the output. Note that the output screen looks identical to the opening screen shown in Figure 2, but has new values based on the input data. The dialogue box in the center offers two options: start the Navigator again, or copy the output data to a separate spreadsheet labeled "Summary".

The computational structure of the program generates an initial output that is loaded into the "Calculation" page. The structure of this page is not totally amenable to subsequent data manipulation operations within the Excel environment. Although the "Calculation" page can be used for sorting data, the totality and nature of the information presented can lead to difficulties and inconsistencies within the sort results. While all of the output data in the "Calculation" page is identical to the data in the "Summary" spreadsheet, the "Summary" page allows all of the sorting and manipulation options of Excel, and; thus, provides a more powerful and convenient environment for navigating through the output data.

Comments Regarding "Summary" Datasheet

The first column of the "Summary" tab, the generalized "Name" appears to be different than the label used in the first column of the "Calculation" worksheet. In fact, "Name" appears in the very last column of the "Calculation" page, and is a way of representing the stiffener spacing and T-beam flange width in inches. This provides a quicker way of representing each solution for further data sorting.

The "Summary" page is presented in three sections:

- "Combined Properties" – overall properties of the of the plate/beam structure (Columns B through K);
- "T Beam Properties" - the sectional properties of each of the stiffeners used in each named option (Columns L through Y); and
- "Analysis Results"– both the "Utilization Factors" – how much of the allowable stresses are actually used in the named option; and the "limiting element" of each option (Columns Z through AE).

This presentation of the information allows many ways to evaluate the various options:

- If overall structural weight is the driver, sort by weight per square foot;
- If section depth is important, a primary sort by depth can be followed by a secondary sort for weight per square foot;
- If maximum efficiency of material is desired, sort by utilization factors;

Of course, there are many other ways to treat the data. If full relational database functions are needed, the data can be loaded in more robust databases such as Microsoft Access™.

Tables I and II below describe all of the input and output data nomenclature, and when appropriate, the standards or criteria from which they are drawn.

Symbols and Definitions:

Table 1 - User Input Nomenclature and Definition

Uniform Load	Uniform load in pounds per square foot
Span	Span or Frame Spacing in feet
Global Deflection Criteria	Global Deflection Criteria (GDC) is the maximum deflection of effective beam. GDC is a function of the span, and expressed maximum deflection equals Span (in)/GLDC.
Local Deflection Criteria	Local Deflection Criteria (LDC) is the maximum deflection of plate between the stiffeners. LDC is a function of the plate thickness, and expressed as maximum deflection equals LDC*plate thickness.
Minimum Plating Thickness Criteria	Minimum Plating Thickness Criteria, coefficients are defined by NVR
Material Selection	Preprogrammed material database
Material Description	User defined material descriptor
Modulus of elasticity	User defined Modulus of Elasticity, input should be in units of psi
Poisson Ratio	User defined Poisson's Ratio, unitless
Yield Stress	User defined Yield Stress, input should be in units of psi
Weight Density	User defined Weight Density, units should be in pounds per cubic inch
Safety Factor	User defined Safety Factor (SF) where SF=Yield Stress/Allowable stress
Minimum Plating C Factor	User defined Minimum Plating C Factor, C Factor is defined by Naval Vessel Rules

Table 2 - Output Nomenclature and Definition

Option	"Place holder" for each allowable solution of the design case
Generalized name	Stiffener spacing and T-beam flange width in inches
Weight Per Sq. Ft.	Combined weight (lb/ft^2.) of the plate and T-Beam section
Center Deflection Ratio	Span (in.) divided by the calculated deflection at center
Local Deflection UF	Utilization Factor (UF) expressed in percent. Calculates what percentage of the allowable plate deflection was used.
Local Stress UF	Utilization Factor (UF) expressed in percent. Calculates what percentage of the allowable plate stress was used.
Web Shear Stress UF	Utilization Factor (UF) expressed in percent. Calculates what percentage of the allowable shear stress in the web was used.
Normal Stress UF	Utilization Factor (UF) expressed in percent. Calculates what percentage of the allowable shear stress in the web was used.
Limiting Element	Plate or Flange is the limiting element for the
Plate Thickness (in)	Minimum required plate thickness.
Lesser Section Modulus (in^3)	Combined effective section modulus
Greater Section Modulus (in^3)	Combined effective section modulus
Effective I (in^4)	Effective area moment of inertia
r (in)	Radius of Gyration for the effective section
YF (in)	Distance from the centroid to the outer fiber of the flange
YP (in)	Distance from the centroid to the outer fiber of the plate
Area (in^2)	Actual area of the combined section
Depth (in)	Depth of the T-Beam, web height plus flange thickness
Flange Width (in)	Width of the flange in inches
Flange Thickness (in)	Thickness of the flange in inches
Shear Area (in^2)	Depth of the T-Beam times the thickness of the web
Weight Per Foot	Weight per linear foot of the T-Beam in pounds
Web Thickness (in)	Thickness of the web element in inches
I Major (in^4)	Area moment of Inertia of the major axis of the T-Beam
S Major (in^3)	Section Modulus of the major axis of the T-Beam
r Major (in)	Radius of Gyration of the major axis of the T-Beam
I Minor (in^4)	Area moment of Inertia of the minor axis of the T-Beam
S Minor (in^3)	Section Modulus of the minor axis of the T-Beam
r Minor (in)	Radius of Gyration of the minor axis of the T-Beam
k (in)	Distance from the outer fiber of the flange to the centroid of the T-Beam
Name	Combined flange width and stiffener spacing
Effective Breadth (in)	Effective breadth of the combined section, minimum of the following three possibilities: One quarter of the span; Stiffener spacing (half on each side of the stiffener); or 2t√(E/Fy) where t is the plate thickness, E is the modulus of elasticity (psi) and Fy is the yield strength of the material.

DSN Program Structure

The iterative process in which the Navigator handles input conditions and makes calculations is delineated in this section. The material is divided into the following parts:

- List and definition of symbols used in subsequent equations;
- Block diagram of program flow; and
- Plating calculation equations.

Where appropriate, the source material is referenced for validation of the approach taken in the equations used by the program.

Symbols and Definitions:

A_{web} is the area of the web
b_{eff} is the effective width of the plating material
b_f is half the flange width
C is the C Factor defined in section 4.2 of reference [6] (unitless)
D is the plate rigidity $\frac{E \cdot t^3}{12 \cdot (1-\nu^2)}$
d_w is the depth of the web element
E is the modulus of elasticity (29,600 ksi)
F_y is the material yield stress
G is the shear modulus
H is the Head of seawater
I_{eff} is the effective area moment of inertia
K is the K Factor defined in section 4.2 of reference [6] (unitless)
L is the free span of the effective beam section
l is the free span between the stiffeners
ν is the Poisson's Ratio (0.3 unitless)
q is the force per unit width (uniformly distributed load)
$S_{greater}$ is the greater section modulus
S_{lesser} is the lesser section modulus
t is the thickness of the plating (inches)
u is a structural parameter (unitless)

Program Flow:
The DNS tool is a macro written for Microsoft Excel 2007 or later. Excel's built-in Visual Basic 6.5 development environment is utilized for this work. Figure 6 presents the program flow diagram for the DNS tool.

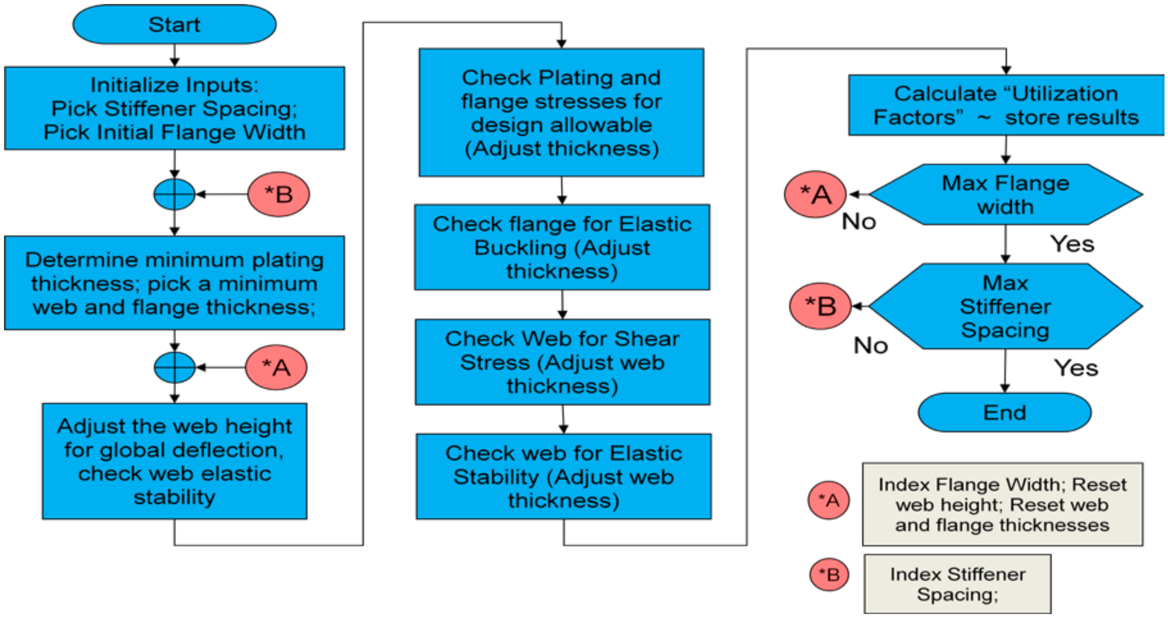


Figure 6 Program Flow Diagram

Plating Calculations:

The program starts by reading in all of the operator entered information and the preprogrammed inputs. The minimum plating thickness is calculated using the following Equation 1. The details are found in section 1.3.4.2 of reference [6].

$$t_{min} = \left(bK\sqrt{H}\right)/_{C}$$

Equation 1

Using the load and assumed stiffener spacing, the stress and deflection of plate is calculated. The plate is modeled assuming cylindrical bending of a uniformly loaded plate with simply supported edges [7].The solution to the differential equations is presented in Equation 2. To determine the maximum stresses and maximum deflection the program must solve for the variable u. One cannot solve for the variable u explicitly. Therefore, a numerical bisection technique called the modified regula falsi method [9] is used to iterate to a solution.

$$\frac{Et^8}{(1-v^2)^2q^2l^8} = \frac{135\tanh(u)}{16u^9} + \frac{27\tanh(u)^2}{16u^8} - \frac{135}{16u^8} + \frac{9}{8u^6}$$

Equation 2

Once u is determined, the maximum stresses and deflection are calculated per the equations below and tested against the predefined input acceptance criteria.

Axial stress in the plate is as follows:

$$\sigma_{axial} = \frac{4u^2 D}{tl^2}$$

Bending stress in the plate is as follows:

$$\sigma_{bending} = \frac{3}{4} q \left(\frac{l}{t}\right)^2 \frac{2\{1 - sech(u)\}}{u^2}$$

Total stress in the plate is as follows:

$$\sigma_{max} = \sigma_{axial} + \sigma_{bending}$$

The maximum plate deflection is calculated as follows:

$$\delta_{plate} = \frac{5ql^4}{384D} \cdot \frac{sech(u) - 1 + \frac{u^2}{2}}{5u^4/24}$$

One the input criteria have been satisfied, the effective breadth of the plating is determined using Equation 3 from references [5],[6]:

$$b_e = min\left\langle \begin{array}{ll} \frac{stiffener\ span}{8} & or \\ 2t\sqrt{E/_{Fy}} & or \\ stiffener\ spacing & \end{array} \right\rangle$$

Equation 3

The effective section is modeled by assuming it is a simply supported uniformly loaded beam. Then, the effective breadth of the plate and an assumed T section is used to determine the effective area moment of inertia, I_{eff}. I_{eff} is calculated using techniques outlined in elementary mechanics texts. It is called the effective area moment of inertia as the effective breadth is used as the width of the top flange of an I-shaped cross section. The maximum deflection of the effective section is determined using Equation 4. The depth of the web is adjusted until the global deflection criteria have been satisfied.

$$\delta_{global} = \frac{5qL^4}{384EI_{eff}} * (1 + \frac{48EI_{eff}}{5GA_{web}L^4})$$

Equation 4

Once the global deflection criteria have been satisfied, the bending stress in the plating and flange elements is calculated using Equation 5:

$$\sigma = \frac{wL^2}{8S_i}$$

$$where\ S_i\ signifies\ the\ greater\ or\ lesser\ section\ modulus$$

Equation 5

The thickness of the plating and flange are adjusted until the predefined strength criteria have been met. Then the bottom flange stability is checked using the following Equation 6 [4]:

$$t_{\min\_flange} = \frac{b_f \sqrt{Fy/1000}}{65}$$

Equation 6

The shear stress in the web is calculated using Equation 7 and compared with the allowable shear stress using Equation 8. The web thickness is adjusted until the strength criteria are met.

$$\tau = \frac{V}{A_{web}}$$

Equation 7

$$\tau_{allow} = min\left\langle \begin{matrix} 0.4 \cdot Fy \\ C_v Fy/2.89 \end{matrix} \right\rangle$$

Equation 8

Details of C_v shown above are found in section F4 pg 5-49 and will not be presented here for brevity. Web stability is checked using Equation 9 [6].

$$t_{\min\_web} = \frac{d_w \sqrt{Fy/1000}}{392}$$

Equation 9

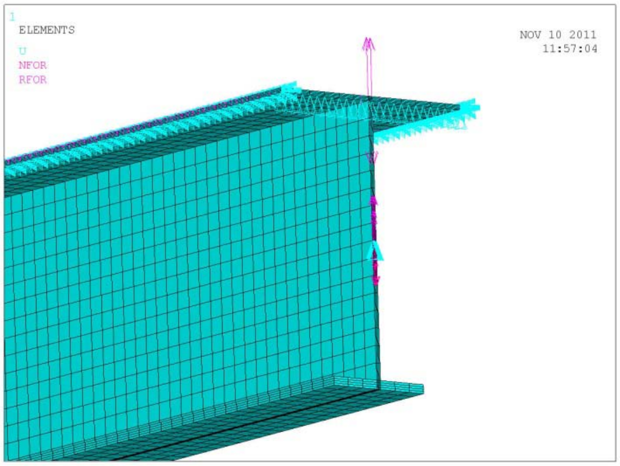
Once all the adjustments have been made we recompute the final effective area moment of inertia, local and global deflections, and stresses. The utilization factors are then calculated, which give the engineer an idea of the structural efficiency and are defined as:

$$UF = \frac{\sigma_{actual}}{\sigma_{allow}}$$

Equation 10

Validation effort

Extensive hand calculations were used during the software development effort. For final verification, the DNS tool output was compared against finite element models.



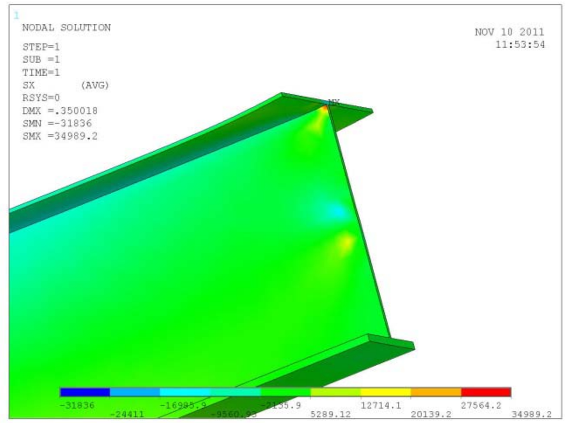


Figure 7. Validation FEA Mesh and Plot used in first validation effort (*courtesy CTC*)

Initial validation with FEA performed at CTC revealed areas in which minor discrepancies occurred. These were attributed to bugs in the program routines, which were easily analyzed and fixed (11). Further validation efforts were performed using FEA routines at HII Ingalls (12). Other areas were noted in this review; and again, the software was checked and corrected. FEA mesh and results typical of this effort are shown in Figure 7.

Examples of final review and validation of the software are shown in Figure 8, below. Three design scenarios were chosen. Each scenario was run using the Design Space Navigator spreadsheet. One beam was selected from each output set.

Each beam was then modeled using NEiNastran FEA software. The beams were modeled using the same properties listed under their respective scenario and properties listed above. The models were constructed using plate elements. Simple supports were represented by a pinned condition on one end and vertical constraint on the other. The uniform deck load was transformed into a linear load per unit length and applied to the plate-web intersection. End constraints were achieved by linking all nodes at the end of the model to a single node near the neutral axis. Constraints were applied to the single node. This creates an end condition similar to those assumed in the analytical beam equations.

Design Scenario 1	
Uniform Pressure	1000 psf
Span	7 ft
Global Deflection	Span / 300
Local Deflection	2X
Min Plate Thickness	Case 1
Material	DH 36

Beam Details	
Plate Thickness (in)	0.313
Spacing (in)	16
Web Depth (in)	4.94
Web Thickness (in)	0.125
Flange Width (in)	2
Flange Thickness (in)	0.188

Results			
	FEA	DSN	% Diff
Deflection (in)	0.211	0.227	7.31%
Shear Stress (ksi)	7.6	7.52	1.06%
Normal Stress (ksi)	35.6	35.8	0.56%

Design Scenario 2	
Uniform Pressure	1500 psf
Span	5 ft
Global Deflection	Span / 500
Local Deflection	3X
Min Plate Thickness	Case 2
Material	DH 36

Beam Details	
Plate Thickness (in)	0.375
Spacing (in)	12
Web Depth (in)	4.13
Web Thickness (in)	0.125
Flange Width (in)	2
Flange Thickness (in)	0.125

Results			
	FEA	DSN	% Diff
Deflection (in)	0.121	0.115	5.08%
Shear Stress (ksi)	7.1	7.3	2.78%
Normal Stress (ksi)	33.4	32.7	2.12%

Design Scenario 3	
Uniform Pressure	2000 psf
Span	10 ft
Global Deflection	Span / 200
Local Deflection	1X
Min Plate Thickness	Case 3
Material	DH 36

Beam Details	
Plate Thickness (in)	0.188
Spacing (in)	6
Web Depth (in)	6.5
Web Thickness (in)	0.125
Flange Width (in)	2
Flange Thickness (in)	0.25

Results			
	FEA	DSN	% Diff
Deflection (in)	0.416	0.443	6.29%
Shear Stress (ksi)	6.4	6.1	4.80%
Normal Stress (ksi)	34.2	35.4	3.45%

Figure 8 Validation Results

The percent difference calculations presented in Figure 8 show reasonable agreement between the DNS and the finite element models. The deflection predictions show the largest disagreement. This disagreement is most likely attributed to slight modeling errors coupled with inaccuracies in the shear shape factor in the beam deflection equation and rounding errors during data reduction.

Future Work

Early in the project, it was apparent that the original conceptual deliverable: a way of replicating the information contained in reference [5] while allowing the freedom to establish design problems and quickly generate a range of acceptable solutions for further evaluation, would be achievable. The current version of the software has achieved this goal. Initial responses to beta testing done internally at ATS and externally by MM and Ingalls have been positive. Thus, further work on the project will include:

- Evaluate "In-Plane" loading scenarios;
- Evaluate user selectable different materials for plate, stiffener web, and stiffener flange;
- Evaluate other materials (e.g., Aluminum, HLSA-115, etc.); and
- Evaluate other shapes such as flat bars, bulb flats, angles, and flanged bars.
- Evaluate the ability for using the software with either English or metric units

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