Guidance Notes for the Classification of Special Service Craft

Calculation Procedures for Composite Construction

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Lloyd's Register

CALCULATION PROCEDURES FOR COMPOSITE CONSTRUCTION

Contents

Introduction

Section

■ Application of procedures

To clarify the procedures contained in the *Rules and Regulations for the Classification of Special Service Craft* (hereinafter referred to as the Rules for Special Service Craft) a series of typical calculation procedures are contained in these 'Guidance Notes'. The procedures describe the fundamental principles contained in Part 8 of the Rules for Special Service Craft and the associated computer software.

The procedures contained in these Guidance Notes are for:
(a) Design of single skin hull laminates.
(b) Design of sandwich panel laminates.
(c) Design of typical stiffening members.

■ Alternative procedures

The procedures describe the Rule method of calculating the various stresses in laminates. Where alternative theoretical methods are to be adopted they are to be in addition to the Rule calculation procedures and the designer is to submit full details of their assumptions and calculation procedures such that the submitted calculations may be validated.

■ Symbols and definitions

All symbols and definitions are as indicated in Pt 8, Ch 3 of the Rules for Special Service Craft.

■ *Section 1* General

1.1 This Section outlines the Rule approach to the design of structural members to be built in FRP and provides example calculations.

1.2 The procedures contained in these Guidance Notes are for:
(a) Design of single skin hull laminates.
(b) Design of sandwich panel laminates.
(c) Design of typical stiffening members.

■ *Section 2* Structural analysis

2.1 The Rules for Special Service Craft provide scantling requirements for a basic structural configuration for both mono and multi-hull craft with multi-deck or single deck hulls which include a double bottom, or a single bottom arrangement. The structural configuration may also include a single or multiple arrangement of cargo hatch openings. The Rules for Special Service Craft provide for both longitudinal and transverse framing systems. Alternative types of framing systems will be specially considered on the basis of the Rules for Special Service Craft.

2.2 Every effort has been taken to make the Rules for Special Service Craft scantling formulae as transparent as possible, and to achieve this objective the following approach has been adopted:
- lay down requirements,
- specify modelling considerations,
- indicate limit states,
- state constraints in an explicit manner.

2.3 This approach will enable the designers and Builders to decide for themselves the suitability of the Rules for Special Service Craft for their project. Further and perhaps more importantly changes may be easily made to the requirements based upon experience gained, discussions with interested parties and as development progresses. This is similar to the current Rule development process which is continually updating and ‘tailoring’ Rule requirements.

■ *Section 3* Fibre composites

3.1 Part 8 of the Rules for Special Service Crafts apply to craft constructed of fibre reinforced plastics using hand lay-up, mechanical deposition, contact moulding techniques or vacuum assisted techniques. Construction may be either single-skin or sandwich construction, or a combination of both. Where moulding techniques and methods of construction differing from those assumed to be used within the Rules for Special Service Craft are proposed, details are required to be submitted for consideration.

3.2 For the purposes of the Rules for Special Service Craft a ‘plastic’ is regarded as an organic substance which may be thermosetting or thermoplastic and which, in its finished state, may contain reinforcements or additives. The quantities of such additives are strictly limited by the Rules for Special Service Craft.

3.3 The resins used in production are to be of a type which have been approved by Lloyd’s Register (hereinafter referred to as LR) for marine construction purposes. Samples of the resin batches being used in the construction may require to be taken for limited quality control examinations.

3.4 All fibre reinforcements are to be of a type approved by LR. The other materials used in the construction of the craft are also to be manufactured and tested in accordance with the requirements of the *Rules for the Manufacture, Testing and Certification of Materials* (hereinafter referred to as the Rules for Materials), of the Rules for Special Service Craft, with particular reference to Chapter 14 for plastics materials.

■ *Section 4* Fibre reinforced composite construction

4.1 The properties of composite sections and laminates are to be determined from the results of test data. The mechanical properties to be used for scantling calculation purposes are to be 90 per cent of the mean first ply/resin cracking failure values determined from accepted mechanical tests. All test pieces are to be representative of the product to be manufactured. This is particularly important since the material of construction is ‘manufactured’ on site, at the same time as the product.

4.2 The mechanical properties of the materials are also to be estimated from the appropriate procedures and formulae contained within the Rules for Special Service Craft. The acceptable design values for glass reinforced polyester resin laminates are not to be greater than those contained with the Rules for Special Service Craft unless agreed otherwise by LR. Additional information on the application of the various formulae is given in these Guidance Notes.

4.3 The various formulae referred to above require that sufficient input data be available which relates to each of the proposed materials. Where it is proposed to use design values greater than the nominal value indicated in the Rules for Special Service Craft the designers and/or Builders should agree the values for use in the scantling analysis with LR at the design stage and prior to the submission of plans and data for appraisal.

4.4 Strength calculations for all advanced fibre composites are to be based on the Rules values and the results of testing of truly representative sections of the proposed design. The sections are to be manufactured under typical production conditions using the same materials, fibre contents, methods of lay-up and time delays. Mechanical testing is, in general, to be based upon the requirements specified in Chapter 14 of the Rules for Materials.

4.5 A through ply analysis is required to be conducted for both plate and stiffener elements and the resultant stresses compared with the allowable stress limits for the particular element. Example procedures are described in these Guidance Notes.

■ *Section 5* Direct calculations

5.1 Direct calculations may be specifically required by the Rules for Special Service Craft. They may be required for craft having novel design features, or may be submitted in support of alternative arrangements and scantlings. LR may, when requested, undertake calculations on behalf of designers or Builders and make recommendations with regard to the suitability of any required model tests. Where model testing is undertaken to complement direct calculations details would normally be required to be submitted indicating the schedule of tests, details of test equipment, input data, analysis and calibration procedures together with tabulated and plotted output.

5.2 All direct calculations are to be submitted for examination. Where calculation procedures other than those available within the Rules for Special Service Craft are employed, supporting documentation is to be submitted for appraisal and this is to include details of the following:

- calculation methods,
- assumptions and references,
- loading data,
- structural modelling,
- design criteria.

5.3 LR will consider the use of Builder's and/or designer's programs for direct calculations in the following cases:

- where it can be established that the program has previously been satisfactorily used to perform a direct calculation similar to that now submitted,
- where sufficient information and evidence of satisfactory performance is submitted to substantiate the validity of the computation performed by the program.

5.4 Where items are of a novel or unconventional design or manufacture, it is the responsibility of the Builder and/or designer to demonstrate their suitability and equivalence to the Rule requirements. Alternative arrangements, which are in accordance with the requirements of a National Authority, may be accepted as equivalent to the requirements of the Rules for Special Service Craft.

5.5 These Guidance Notes are published to enable designers/Builders to carry out the Rule calculations without using the Rules for Special Service Craft software.

Section

Section 1 **Calculation procedure**

1.1 The stress in individual plies of a laminate is calculated in accordance with Pt 8, Ch 3,1.12 of the Rules for Special Service Craft, based on bending moment (*see* 1.9) and the laminate stiffness of a 1 cm wide elemental strip of material.

1.2 Considering the model shown in Figs. 2.1.1 and 2.1.2 of a typical single skin hull laminate. Assume a pressure of 33 kN/m^2 and that there is no significant panel curvature.

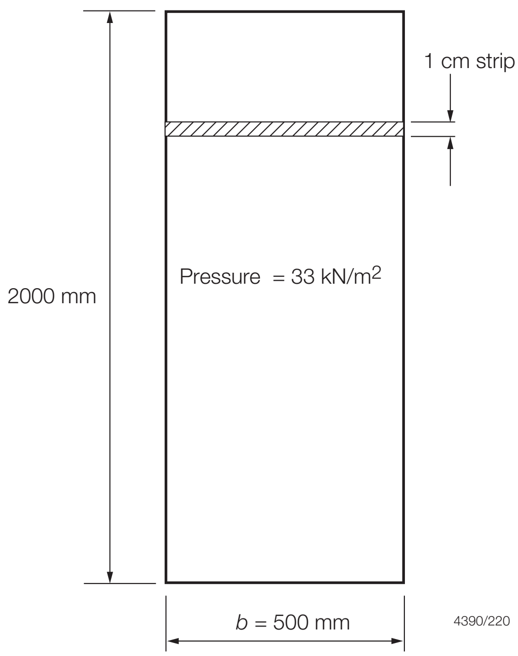

Fig. 2.1.1 Single skin example model

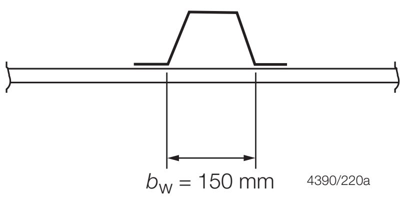

Fig. 2.1.2 'Top-hat' stiffener used in model

1.3 In this example the maximum bending moment is determined from Pt 8, Ch 3,1.9 of the Rules for Special Service Craft and occurs under the web at the base of the stiffener. It should be noted that no reduction in the bending moment, M_b, due to aspect ratio effect is given since the panel aspect ratio, i.e. panel length/panel breadth is greater than 2. *See* Pt 8, Ch 3,1.10.1 of the Rules for Special Service Craft.

$$\gamma = \frac{b_w}{b} = \frac{150}{500} = 0,3$$

$$k = \frac{\gamma^3 + 1}{\gamma + 1} = 0,79$$

$$M_b = \frac{k\,p\,b^2}{12} \times 10^{-5} \text{ Nm}$$

$$= \frac{0,79}{12} \times 33 \times 500^2 \times 10^{-5}$$

$$= 5,43 \text{ Nm.}$$

1.4 The laminate section modulus calculation is shown in Table 2.1.1 at the end of this Section. From Fig. 2.1.3 it will be noted that there will be positions where tension and compression considerations will apply. Such calculations are ideally suited to computer based investigation.

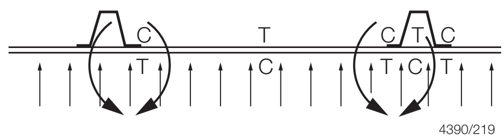

Fig. 2.1.3
Regions of tension (T) and compression (C) in example model

1.5 In order to apply a more detailed investigation it is necessary to establish the position of the neutral axis. However, in relatively balanced laminates this may be assumed to be at mid-depth. The procedure is simply to carry out the calculations assuming compressive properties on one face and tensile properties on the other face. Subsequently, the properties should be reversed and the layer stress calculations repeated. The calculated values should then be compared with the appropriate ultimate properties, i.e., dependent upon whether tension or compression considerations apply.

1.6 In the example the moments were evaluated about the base, which was taken to be the outer (wet) surface. The stiffness, EI, per 1 cm width, about the neutral axis, is determined using the parallel axis theorem:
In general:

$$I_{na} = I_{xx} - Ay^2$$

$$EI_{sect} = \Sigma\, EI_{base} - (\Sigma\, Et) \times 10 \times y^2$$

where

y = distance of neutral axis above the base (mm).

Table 2.1.1 Tabulation of single skin laminate calculations

	Ply No.	Description	G_c	Weight (g/m^2)	t (mm)	Lever @ base, x (mm)	E (N/mm^2)	$E.t$	$E.t.x$	I @ base	EI @ base
Dry, *see* Note	1	CSM	0,33	600	1,250	10,149	7200	9000	91341	1289,2	9281917
	2	CSM	0,33	600	1,250	8,899	7200	9000	80091	991,5	7139017
	3	CSM	0,33	600	1,250	7,649	7200	9000	68841	733,0	5277367
	4	CSM	0,33	600	1,250	6,399	7200	9000	57591	513,5	3696967
	5	WR	0,5	600	0,734	5,407	14000	10276	55562	214,9	3008869
	6	CSM	0,33	600	1,250	4,415	6950	8688	38355	245,3	1704699
	7	CSM	0,33	600	1,250	3,165	6950	8688	27496	126,8	881558
	8	WR	0,5	600	0,734	2,173	14500	10643	23127	35,0	507333
	9	CSM	0,33	600	1,250	1,181	6950	8688	10260	19,1	132482
Wet (*see* Note)	10	CSM	0,286	225	0,556	0,278	6290	3497	972	0,6	3604
TOTALS					10,774			86479	453637		31633812

NOTE
'Dry' indicates the inner surface of the hull and 'wet' the outside of the shell laminate.

Position of neutral axis above base = $\dfrac{453637}{86479}$ = 5,246 mm

Tensile modulus of section = $\dfrac{86479}{10,774}$ = 8027 N/mm^2

Stiffness *EI* about neutral axis = 783,8 N cm^4/mm^2 (based on 1 cm wide strip)

1.7 A factor of 10 (width in mm) is introduced to correct the value of area used in the parallel axis theorem, since a 1 cm wide strip of material is considered in the calculations.

From the tabulation:

$$EI_{sect} = 31633812 - (86479 \times 10 \times 5{,}246^2)$$
$$= 7837614 \text{ Nmm}^4/\text{mm}^2$$
$$= 783{,}8 \text{ Ncm}^4/\text{mm}^2.$$

1.8 From Pt 8, Ch 3,1.12 of the Rules for Special Service Craft the individual layer stresses (tensile consideration) are determined from:

$$\sigma_{ti} = \frac{E_{ti}\, y_i\, M}{\Sigma\,(E_i\, I_i)} \times 10^{-1} \text{ N/mm}^2$$

1.9 More generally, the calculation of the stresses in individual layers becomes:

$$\sigma_{ti} = \frac{5{,}43}{783{,}8} \times E_i\, y_i \times 10^{-1} \text{ N/mm}^2$$
$$= 693 \times 10^{-6} \times E_i\, y_i \text{ N/mm}^2$$

where

E_i = E_{ti} or E_{ci} for the ply relative to its position above or below the neutral axis

y_i = distance from the neutral axis to the outer extremity of an individual ply, *i*, in mm.

1.10 Consider the following typical arrangement and the associated stresses for a single shell panel outside of the slamming zone:

Consider the outer (wet) surface:

Consider the 225g/m^2 chopped strand mat reinforcement in tension:

$$\sigma_{ti} = 693 \times 10^{-6} \times E_i\, y_i$$
$$= 693 \times 10^{-6} \times 6290 \times 5{,}246$$
$$= 22{,}9 \text{ N/mm}^2.$$

From Pt 8, Ch 3, Table 3.1.1 of the Rules for Special Service Craft.

$\sigma_{ult\ tension}$ = 82,2 N/mm^2 for CSM at G_c =0,286

Hence, stress fraction = 22,9/82,2 = 0,278.

1.11 From Table 7.3.1 in Pt 8, Ch 7 of the Rules for Special Service Craft, the limiting tensile stress fraction is 0,33 for the side shell outside of the slamming zone. Hence, the calculated stress fraction is lower than the limiting stress factor and is therefore acceptable.

1.12 Similarly, consider the 600g/m^2 woven roving reinforcement in tension:

$$\sigma_{ti} = 693 \times 10^{-6} \times E_i\, y_i$$
$$= 693 \times 10^{-6} \times 14500 \times (5{,}246 - 0{,}556 - 1{,}25)$$
$$= 34{,}6 \text{ N/mm}^2$$

$\sigma_{ult\ tension}$ = 190 N/mm^2 for woven roving at G_c = 0,5

Stress fraction = 34,6/190 = 0,182

Hence acceptable.

1.13 Consider the inner (dry) surface:

The 600 g/m^2 chopped strand mat reinforcements at the inner surface in compression:

$$\sigma_{ci} = 693 \times 10^{-6} \times E_i\, y_i$$
$$= 693 \times 10^{-6} \times 7200 \times (10{,}774 - 5{,}246)$$
$$= 27{,}6 \text{ N/mm}^2$$

$\sigma_{ult\ comp}$ = 122 N/mm^2 for CSM at G_c = 0,33

Stress fraction = 27,6/122 = 0,226

Hence acceptable.

■ *Section 2*
Concluding remarks

2.1 From the example, the highest stress factor occurs in the outer 225 g/m^2 chopped strand mat reinforcement (in tension) but this is significantly lower than the limiting stress fraction required by the Rules. The bending moment at the centre of the panel is smaller than that at the boundary and consequently, the stress factor will be correspondingly reduced. The design may be optimised by sequentially removing plies, changing reinforcement weights and/or by providing receiving strips under the base of the 'top-hat' stiffeners.

2.2 For the design of side shell laminates there are no shear and deflection criteria to be fulfilled. In this example a significant reserve exists between the actual and the ultimate stresses.

2.3 It is of paramount importance that the strain compatibility of the component materials is carefully considered.

2.4 Consider typical values of apparent strain, ε_a, at failure for the following materials in laminate form:

	Tension	Compression
'E' glass	1,3%	1,05%
Carbon fibre	0,9%	0,55%
Aramid fibre	1,3%	0,60%

2.5 The actual strain permissible is controlled by the material with the lowest apparent strain. The level of strain depends upon whether the reinforcements are in tension or compression and depends on their relative positions within the laminate. Consequently if, for example, a carbon fibre reinforcement is used in the outer plies of laminate then the strain must be constrained to a maximum of 0,33 x 0,9 per cent, i.e., 0,297 per cent. Therefore, the corresponding allowable stress in the other reinforcements must be related to the strain in the reinforcement relative to its position away from the neutral axis and that of the carbon fibre reinforcement, e.g.:

$$\varepsilon_{limitCSM} = \frac{\varepsilon_{allowable\ carbon} \times y_{CSM}}{y_{carbon}}$$

2.6 Where aramid reinforcements are being used, special consideration must be given to the compressive properties. For comparison purposes aramid reinforcements, at a fibre content of 0,45 (by weight), typically have the following properties:

	Tension	Compression
Ultimate strength (N/mm^2)	300	100
Elastic modulus (N/mm^2)	21000	17000

2.7 The radical reduction in ultimate compressive strength may prove to be unacceptable on the inside at the panel boundaries or on the outside at the panel centre. Designs which feature aramid fibres in the outer plies, in an attempt to make use of the superior impact properties, must be checked at the panel centre for compression in the individual layers. This also applies to hybrid reinforcements containing aramid fibres. These reinforcements have one off properties of higher than one of the constituent fibres however, in service the individual allowable strains for each fibre reinforcement should not be exceeded.

Section

■ *Section 1* Calculation procedure

1.1 Consider the model of a side shell sandwich panel having dimensions 700 mm x 2000 mm shown in Fig. 3.1.1. Assume a design pressure of 50 kN/m^2 and a panel of negligible curvature.

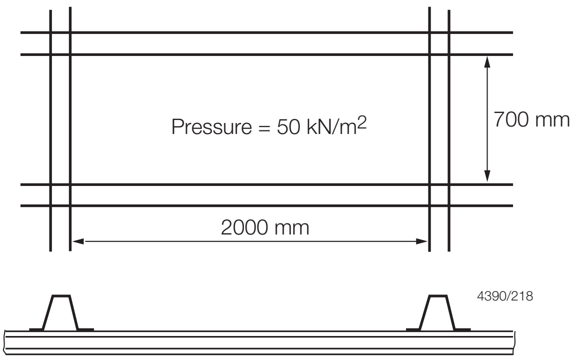

Fig. 3.1.1 Sandwich panel laminate example model

1.2 The panel is to be designed in accordance with the requirements of Pt 8, Ch 3 of the Rules for Special Service Craft. Firstly it is necessary to estimate the core thickness using Pt 8, Ch 3,1.13.2 of the Rules for Special Service Craft assuming a nominal value of tensile modulus of 11000 N/mm^2 for sandwich panel facings:

$$t_s = \phi\, k_s\, b \sqrt[3]{\frac{p}{E_{tpS}}} \quad \text{mm}$$

$$= 0{,}144 \times 700 \times \sqrt[3]{\frac{50}{11000}}$$

$$= 16{,}7 \text{ mm}$$

Hence, select 20 mm core as a typically available size.

1.3 From Pt 8, Ch 3,1.13.9 of the Rules for Special Service Craft the maximum core shear at the mid-point along the edge of the sandwich panel is given by:

$$\tau_c = \frac{p\, b\, k_S}{2 t_c} \times 10^{-3} \quad \text{N/mm}^2$$

$$= \frac{50 \times 700 \times 1}{2 \times 20} \times 10^{-3}$$

$$= 0{,}875 \text{ N/mm}^2$$

1.4 The panel aspect ratio correction factor is given in Pt 8, Ch 3,1.13.9 of the Rules for Special Service Craft. A_R = 2000/700 = 2,86, hence k_S = 1.
No correction factor applied since $A_R > 2$.

1.5 To achieve an allowable shear stress fraction of 0,30, *see* Pt 8, Ch 7,3.5 of the Rules for Special Service Craft, this design would require the selection of 200 kg/m^3 foam core. Clearly being unacceptable the conclusion is to adopt a 50 mm thick core to reduce the core shear stress. The stress varies inversely with core thickness:

$$\tau_{50} = \tau_{20} \times \frac{20}{50} = 0{,}35 \quad \text{N/mm}^2.$$

1.6 To achieve the required allowable shear stress fraction the foam core must have a core shear strength of 0,35/0,30 = 1,17 N/mm^2. This may be achieved using a 100 kg/m^3 foam core using 90 per cent of the manufacturer's quoted value.

1.7 However, there are numerous solutions to achieve an acceptable arrangement. The options include:
(a) Repositioning the stiffeners to reduce panel sizes.
(b) Inclusion of shear ties in accordance with Pt 8, Ch 3,1.13.10 of the Rules for Special Service Craft.
(c) Accept the higher density core solution.

1.8 From Pt 8, Ch 3,1.13.3 of the Rules for Special Service Craft the skin thicknesses may be re-calculated allowing for the change in core thickness:

$$t_S = \phi_2 \frac{p\, b^3}{E_{tps}\, t_c^2} \times 10^{-3} \quad \text{mm}$$

$$t_{inner} = 0{,}446 \times \frac{50}{11000} \times \frac{700^3}{50^2} \times 10^{-3} = 0{,}28 \text{ mm}$$

$$t_{outer} = 0{,}594 \times \frac{50}{11000} \times \frac{700^3}{50^2} \times 10^{-3} = 0{,}37 \text{ mm}$$

Clearly, the increase in core thickness gives a substantial increase in panel stiffness. Consequently the skin thicknesses default to the minimum requirement quoted in Pt 8, Ch 3,3.5.5 of the Rules for Special Service Craft. The minimum side shell sandwich skin thicknesses are:

Outer 4 mm
Inner 3 mm.

1.9 The minimum skin thicknesses relate to an assumed fibre content, f_c, of 0,5. Where the fibre content by weight is less than 0,5 the required minimum thickness are to be determined from Pt 8, Ch 3,2.4.2 of the Rules for Special Service Craft.

1.10 In order to comply with the Rules for Special Service Craft, chopped strand mat reinforcements are required against the core. The initial proposal to meet the requirement, features such CSM reinforcements together with a CSM against the gel coat surface.

1.11 The proposed sandwich skin laminate schedule for the outer skin is:

1 x 450 g/m^2 CSM @ G_c = 0,286	= 1,112 mm
3 x 600 g/m^2 WR @ G_c = 0,5	= 2,202 mm
1 x 300 g/m^2 CSM @ G_c = 0,33	= 0,625 mm
Total outer skin thickness	= 3,94 mm
Total reinforcement weight	= 2550 g/m^2

1.12 By transforming the relationship given in Pt 8, Ch 3,1.6.1 of the Rules for Special Service Craft the equivalent fibre content by weight, f_c, is 0,42.
The adjusted minimum skin thickness for the outer skin is:

$$t_{outer} = t_{0,5}\,(1,65 - 1,3 f_c)$$
$$= 4 \times (1,65 - 1,3 \times 0,42)$$
$$t_{outer} = 4,42 \text{ mm.}$$

1.13 The proposed outer skin is deficient by 4,42 – 3,94 = 0,48 mm. Hence one additional woven roving reinforcement may be added to achieve the minimum requirement. The actual thickness of outer skin is 4,67 mm.

1.14 The proposed sandwich skin laminate schedule for the inner skin is:

1 x 300 g/m^2 CSM @ G_c = 0,33	= 0,625 mm
4 x 600 g/m^2 WR @ G_c = 0,5	= 2,936 mm
Total inner skin thickness	= 3,56 mm
Total reinforcement weight	= 2700 g/m^2

The equivalent overall fibre content of the inner skin is 0,473.
The adjusted minimum skin thickness for the inner skin is:

$$t_{inner} = t_{0,5}\,(1,65 - 1,3 f_c)$$
$$= 3 \times (1,65 - 1,3 \times 0,473)$$
$$t_{inner} = 3,1 \text{ mm.}$$

1.15 The proposed arrangement which meets both core shear and minimum sandwich skin requirements is given in Table 3.1.1.

Table 3.1.1 Tabulation of sandwich panel calculations

	Ref No.	Description	G_c	Weight (g/m^2)	*t* (mm)	Lever @ base, *x* (mm)	*E* (N/mm^2)	*E.t*	*E.t.x*	*I* @ base	*EI* @ base
Inner skin	1	WR	0,5	600	0,734	57,87	14000	10276	594641	24579	344105690
	2	WR	0,5	600	0,734	57,13	14000	10276	587099	23959	335431718
	3	WR	0,5	600	0,734	56,40	14000	10276	579556	23348	326868472
	4	WR	0,5	600	0,734	55,67	14000	10276	572014	22744	318415951
	5	CSM	0,33	300	0,625	54,99	7200	4500	247435	18896	136054699
Core	6	100 kg/m^3	–	–	50,000	29,67	83,7	4185	124182	544410	45567128
	7	CSM	0,33	300	0,625	4,36	6950	4344	18941	119	827333
	8	WR	0,5	600	0,734	3,68	14500	10643	39177	100	1446879
	9	WR	0,5	600	0,734	2,95	14500	10643	31365	64	929103
	10	WR	0,5	600	0,734	2,21	14500	10643	23553	36	526005
Outer skin	11	WR	0,5	600	0,734	1,48	14500	10643	15741	16	237588
	12	CSM	0,286	450	1,112	0,56	6290	6994	3889	5	28830
TOTALS					58,23			103699	2837592		1510439396

Inner skin in compression/outer skin in tension.

Position of neutral axis above base = $\dfrac{2837592}{103699} = 27,36$ mm

Tensile modulus of elasticity of section = $\dfrac{103699 - 4185}{58,234 - 50} = \dfrac{99514}{8,234} = 12086$ N/mm^2

Stiffness *EI* about neutral axis = 73397 N cm^4/mm^2 per 1 cm wide strip

Section 2
Deflection of sandwich panel

2.1 Consider the revised model shown in Fig. 3.2.1:

E_{ms} = 12086 N/mm^2 from Table 3.1.1

b = breadth in direction of bending = 700 mm

G = shear modulus for 100 kg/m^3 core
= 36 N/mm^2 being 90 per cent of the manufacturer's quoted value

t_s = mean skin thickness
(3,56 + 4,67)/2 = 4,11 mm

$(1 - v_f^2)$ = unity (approximately)

Calculation of deflection in accordance with Pt 8, Ch 3,1.13.15 of the Rules for Special Service Craft

$$\delta = \frac{p\,b^2}{8t_c}\left(\frac{b^2}{24E_{ms}\,t_s\,t_c} + \frac{1}{G}\right) \text{x } 10^{-3} \text{ mm}$$

$$= \frac{50 \text{ x } 700^2}{8 \text{ x } 50}\left(\frac{700^2}{24 \text{ x } 12086 \text{ x } 4{,}11 \text{ x } 50} + \frac{1}{36}\right) \text{x } 10^{-3} \text{ mm}$$

= 61,25 x (0,00822 + 0,0278)

= 2,2 mm total deflection.

2.2 The total deflection comprises 23 per cent due to bending and 77 per cent due to shear.

The deflection criterion is given in Table 7.2.1 in Pt 8, Ch 7 of the Rules for Special Service Craft.

$$\delta_{RULE} < \frac{b}{100} \quad \text{where} \quad \frac{b}{100} = 7 \text{ mm}$$

Hence the 2,2 mm total deflection is acceptable.

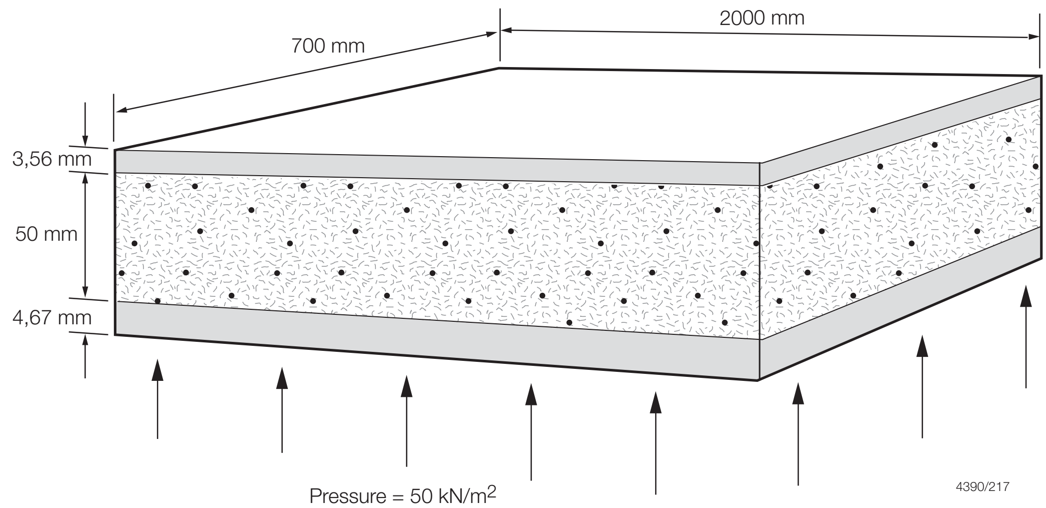

Fig. 3.2.1 Sandwich panel example model

Section 3
Bending moment applied

3.1 The bending moment to be applied at 1 cm width of the sandwich panel is given by Pt 8, Ch 3,1.9 of the Rules for Special Service Craft. In this example it is evident that the maximum bending moment and hence maximum stress occurs under the base of the stiffener. Due to the high aspect ratio no correction factor needs to be applied to modify the applied bending moment.

$$\gamma = \frac{b_w}{b} = \frac{150}{700} = 0{,}2143$$

$$k = \frac{\gamma^3 + 1}{\gamma + 1} = 0{,}8316$$

$$M_b = \frac{k\,p\,b^2}{12} \times 10^{-5} \text{ Nm}$$

$$= \frac{0{,}8316}{12} \times 50 \times 700^2 \times 10^{-5}$$

$$= 17 \text{ Nm.}$$

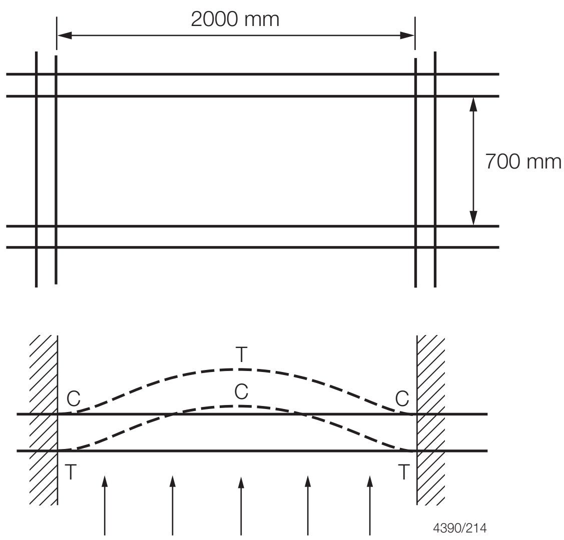

Fig. 3.4.1
Regions of tension (T) and compression (C) in example model

Section 4
Stresses in facings

4.1 Consider the revised model, *see* Fig 3.4.2, with 50 mm thick and 100 kg/m^3 density core having the proposed side shell sandwich skins which comply with the Rules for Special Service Craft minimum requirements. As indicated in Fig. 3.4.1 there will be positions where tension and compression considerations will apply. The relevant elastic modulus has been applied to the element dependent upon its relative position in the sandwich. The proposed schedule together with the tabular calculations are given in Table 3.1.1. Such calculations are ideally suited to computer based investigation.

4.2 The stiffness, EI, per 1 cm width is determined using the parallel axis theorem:
In general,

$$I_{na} = I_{xx} - Ay^2$$
$$EI_{sect} = \Sigma\, EI_{base} - (\Sigma\, Et) \times 10 \times y^2$$

where

y = distance of neutral axis above base (mm).

4.3 It should be noted that the factor 10 (width in mm) is introduced to correct the value of area used in the parallel axis theorem, since a 1 cm wide strip of material is considered in the calculations.

From the tabulated calculations the overall stiffness of the section is calculated:

$$EI_{sect} = 1510439396 - (103699 \times 10 \times 27{,}36^2)$$
$$= 1510439396 - 776259189 \text{ Nmm}^4/\text{mm}^2$$
$$= 734200000 \text{ Nmm}^4/\text{mm}^2$$
$$= 73{,}4 \times 10^3 \text{ Ncm}^4/\text{mm}^2.$$

4.4 From Pt 8, Ch 3,1.13.7 of the Rules for Special Service Craft the individual layer stresses are determined from:

$$\sigma_{ti} = \frac{E_{ti}\, y_i\, M}{\Sigma\,(E_i\, I_i)} \times 10^{-1} \text{ N/mm}^2$$

The calculation of the tensile stress in the individual layers becomes:

$$\sigma_{ti} = \frac{17{,}0}{73{,}4 \times 10^3} \times E_{ti}\, y_i \times 10^{-1} \text{ N/mm}^2$$

$$\sigma_{ti} = 23{,}2 \times 10^{-6} \times E_i\, y_i \text{ N/mm}^2$$

where

E_i = modulus of elasticity of layer (N/mm^2)
y_i = distance of layer from the neutral axis (mm).

4.5 Consider the model as shown in Fig. 3.4.1.

4.5.1 Consider wet surface in tension at the panel boundary:

(a) Consider the CSM reinforcement in the outer ply (450 g/m^2 and G_c = 0,286)

$$\sigma_{CSMult} = 82{,}2 \text{ N/mm}^2$$
$$E_t = 6290 \text{ N/mm}^2$$
$$y_i = 27{,}36 \text{ mm}$$
$$\sigma_{CSM} = 23{,}2 \times 10^{-6}\, E_t\, y_i \text{ N/mm}^2$$
$$= 23{,}2 \times 10^{-6} \times 6290 \times 27{,}36 \text{ N/mm}^2$$
$$= 3{,}99 \text{ N/mm}^2$$

Stress factor = 3,99/82,2 = 0,05 < 0,33 hence accept.

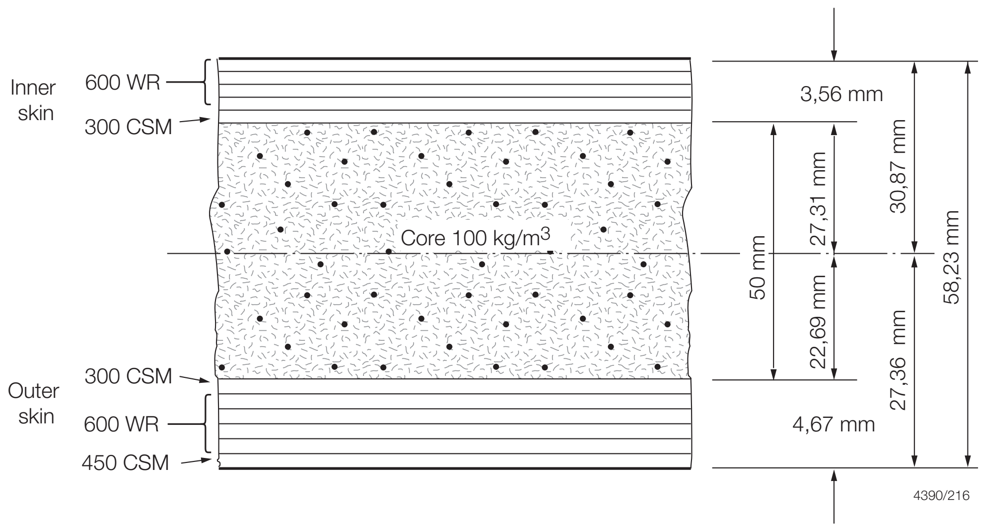

Fig. 3.4.2 Sandwich skin laminate details

(b) Consider the WR reinforcement in the in outer plies (600 g/m^2 and G_c = 0,5)

σ_{WRult} = 190 N/mm^2
E_t = 14500 N/mm^2
y_i = 27,36 – 1,112 = 26,25 mm
σ_{WR} = 23,2 x 10^{-6} E_t y_i N/mm^2
= 23,2 x 10^{-6} x 14500 x 26,25 N/mm^2
= 8,83 N/mm^2

Stress factor = 8,83/190 = 0,046 < 0,33 hence accept.

4.5.2 Consider inner surface in compression at the panel boundary:

(a) Consider top WR reinforcement in compression (600 g/m^2 and G_c = 0,5)

σ_{WRult} = 147 N/mm^2
E_c = 14000 N/mm^2
y_i = 58,23 – 27,36 = 30,87 mm
σ_{WR} = 23,2 x 10^{-6} E_c y_i N/mm^2
= 23,2 x 10^{-6} x 14000 x 30,87 N/mm^2
= 10,03 N/mm^2

Stress factor = 10,03/147 = 0,068 < 0,33 hence accept.

(b) Consider CSM reinforcement in compression (300 g/m^2 and G_c = 0,33)

σ_{CSMult} = 122 N/mm^2
E_c = 7200 N/mm^2
y_i = 30,87 – (4 x 0,734) = 27,93 mm
σ_{CSM} = 23,2 x 10^{-6} E_c y_i N/mm^2
= 23,2 x 10^{-6} x 7200 x 27,93 N/mm^2
= 4,67 N/mm^2

Stress fraction = 4,67/122 = 0,038 < 0,33 hence accept.

4.6 Stress fractions in this example are considerably lower than those required by the Rules for Special Service Craft and it is evident that the design is controlled by and core shear considerations and minimum skin thickness requirements.

4.7 As indicated in Chapter 2, Sections 2.4 to 2.7 of these Guidance Notes for Single Skin Laminates, consideration must be given to the strain compatibility of the reinforcements incorporated in the sandwich skins.

■ *Section 1* Calculation procedure

1.1 Assume a design pressure of 70 kN/m^2 applied to a fully fixed bottom longitudinal located outside of the slamming zone as shown in Fig. 4.1.1.

1.2 The bending moment is determined from Pt 8, Ch 3,1.14.1 of the Rules for Special Service Craft. For a fully fixed stiffener the maximum bending moment coefficient from Table 3.1.5(a) in Pt 8, Ch 3 of the Rules for Special Service Craft is 1/12.

1.3 Hence, maximum bending moment, M_s, is given by:

$$M_s = \frac{s\, l_e^2\, p}{12} \text{ Nm}$$

$$M_s = \frac{500 \times l^2 \times 70}{12} \text{ Nm}$$

$$M_s = 2917 \text{ Nm}$$

Assumed shell laminate:

5 x 800/300 combination mats

G_c = 0,5 (WR in combination mat)
t_{WR} = 0,979 mm
E_t = 14500 N/mm^2

G_c = 0,33 (CSM in combination mat)
t_{CSM} = 0,625 mm
E_t = 6950 N/mm^2

1 x 450 CSM adjacent to gel coat

G_c = 0,286
t_{CSM} = 1,112 mm
E_t = 6290 N/mm^2

Total thickness, t_p = 9,132 mm

The effective width of attached plating $2b_1$ from Pt 8, Ch 3,1.7.1 of the Rules for Special Service Craft for single skin construction is:

$$b_1 = 0{,}5b_w + 10t_{ap}$$
$$= 0{,}5 \times 120 + 10 \times 9{,}132$$
$$= 151 \text{ mm}$$

Hence, apply 302 mm attached plating.

Consider typical layup over ‘top hat’ stiffener:

450 g/m^2 CSM @ G_c = 0,33 – first ply over former
800 g/m^2 WR @ G_c = 0,5
800 g/m^2 WR @ G_c = 0,5
600 g/m^2 UDT @ G_c = 0,54
600 g/m^2 UDT @ G_c = 0,54
800 g/m^2 WR @ G_c = 0,5
800 g/m^2 WR @ G_c = 0,5 – top ply

1.4 Consider the idealised section shown in Fig. 4.1.2.

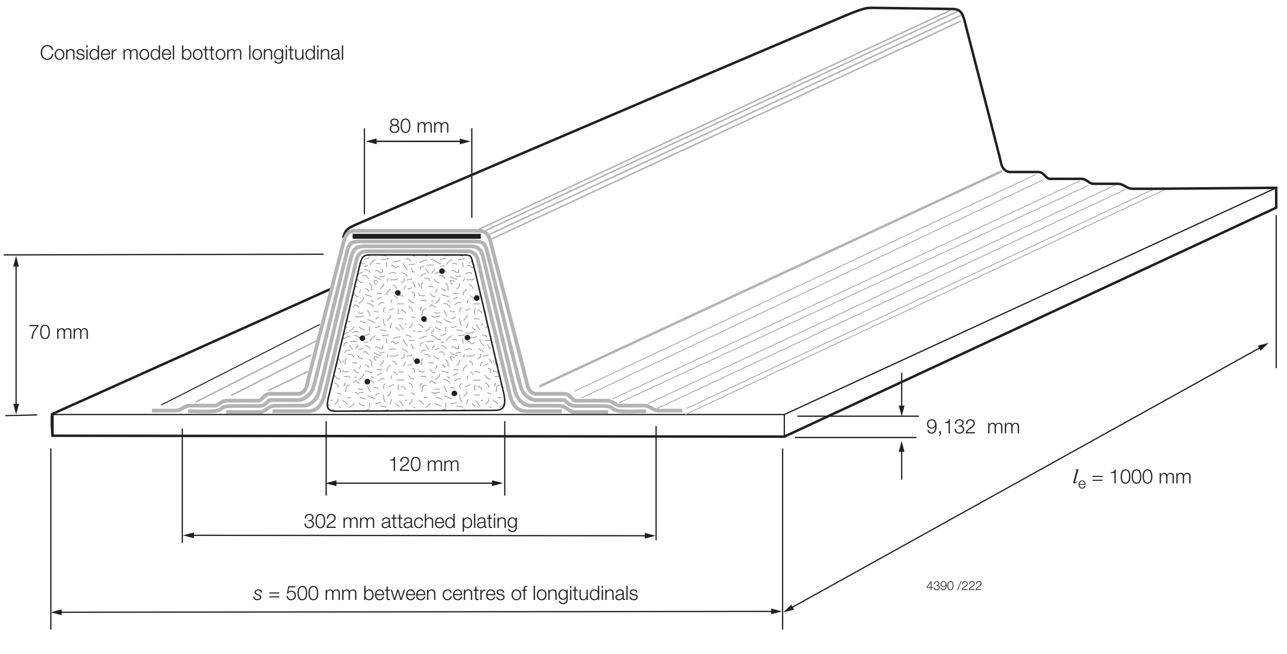

Fig. 4.1.1 ‘Top-hat’ stiffener example model

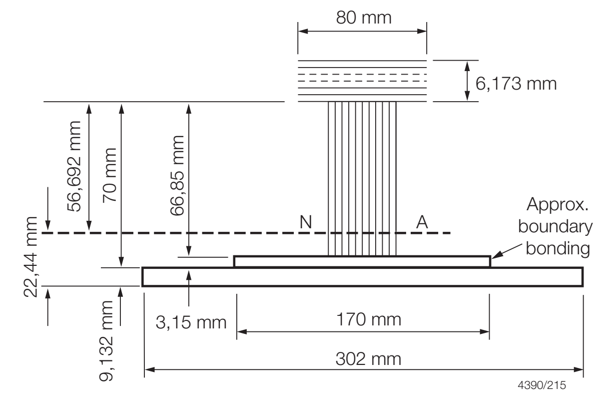

Fig. 4.1.2 Idealised section

1.5 The stiffener bonding is to be in accordance with Pt 8, Ch 3,1.18.6 of the Rules for Special Service Craft and a typical arrangement is shown in Fig. 4.1.3. To simplify the calculation of the stiffness of the overall section the tapered bonding is assumed to be an effective constant thickness. The effective thickness of the bonding is calculated as:

$$t_{bb} = \frac{(4{,}853 \text{ x } 25) + (4 + 3 + 2 + 1) \text{ x } 0{,}079 \text{ x } 15}{25 + (4 \text{ x } 15)}$$

$$t_{bb} = \frac{268{,}2}{85} = 3{,}15 \text{ mm}$$

The boundary bonding may be approximated to a thickness of 3,15 mm over an (85 x 2) mm width to account for both flanges. The majority of the flange comprises of woven rovings and it may be assumed that the tensile modulus is 145000 N/mm^2. The discrepancy is negligible since the element is very close to the neutral axis.

The effective depth and width of the web used in the idealised section are:

$$\begin{aligned} d_{web} &= 70 - \text{effective thickness on bonding} \\ &= 70 - 3{,}15 \\ &= 66{,}85 \text{ mm} \\ t_{web} &= 2 \text{ x } (0{,}937 + 4 \text{ x } 0{,}979) \\ &= 2 \text{ x } 4{,}853 \\ &= 9{,}706 \text{ mm} \end{aligned}$$

Now the web consists of two types of reinforcements, namely one ply of CSM and four plies of woven rovings. The majority of the web will be in compression and the overall modulus of elasticity may be calculated in accordance with Pt 8, Ch 3,1.13.5 of the Rules for Special Service Craft.

$$E_{web} = \frac{\Sigma\,(E_{ci}\,t_i)}{\Sigma\,t_i}$$

$$E_{web} = \frac{(0{,}937 \text{ x } 7200) + (0{,}979 \text{ x } 4 \text{ x } 14000)}{0{,}937 + (0{,}979 \text{ x } 4)}$$

$$E_{web} = 12687 \text{ N/mm}^2$$

The web may now be treated as a single laminate item having an overall compressive modulus, given above.

1.6 The laminate section modulus calculation is shown in Table 4.1.1. The tabulation consists of each element having the compressive moduli in the section above the neutral axis and tensile moduli below. The actual breadth of each element must be entered to calculate the overall section properties. The tabulation corresponds to the idealised section in Fig. 4.1.2.

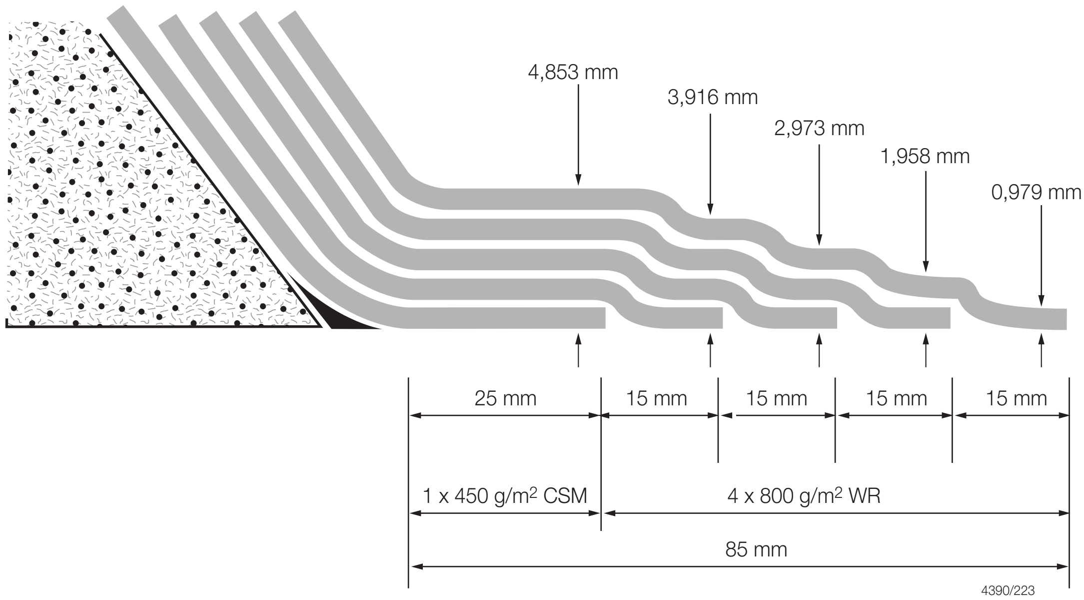

Fig. 4.1.3 Typical stiffener bonding arrangement

Table 4.1.1 Initial tabulation of 'top-hat' stiffener calculations

	Ply No.	Description	G_C	Weight (g/m^2)	t (mm)	Breadth, b (mm)	Lever @ base, x (mm)	E (N/mm^2)	$t.b$	$E.t.b$	$E.t.b.x$	I @ base	EI @ base
Dry, *see* Note	1	WR	0,5	800	0,979	80	84,816	14000	78,32	1096480	92998499	563414,4	7887801805
	2	WR	0,5	800	0,979	80	83,837	14000	78,32	1096480	91925046	550483,0	7706761655
	3	UDT	0,54	600	0,660	80	83,017	20748	52,80	1095494	90944659	363890,1	7549992490
	4	UDT	0,54	600	0,660	80	82,357	20748	52,80	1095494	90221632	358127,2	7430422738
	5	WR	0,5	800	0,979	80	81,538	14000	78,32	1096480	89404238	520706,1	7289885632
	6	WR	0,5	800	0,979	80	80,559	14000	78,32	1096480	88330784	508277,4	7115883045
	7	CSM	0,33	450	0,937	80	79,601	7200	74,96	539712	42961345	474970,0	3419784035
	8	Web	0,5	–	66,85	9,706	45,707	12687	648,85	8231910	376255932	1597160,7	20263177372
	9	bonding	0,5	–	3,15	170	10,707	14500	535,50	7764750	83137178	61832,4	896570245
	10	WR	0,5	800	0,979	302	8,643	14500	295,66	4287041	37050752	22107,1	320553529
	11	CSM	0,33	300	0,625	302	7,840	6950	188,75	1311813	10285266	11609,3	80684330
	12	WR	0,5	800	0,979	302	7,039	14500	295,66	4287041	30174338	14670,7	212724485
	13	CSM	0,33	300	0,625	302	6,236	6950	188,75	1311813	8181119	7347,4	51064249
	14	WR	0,5	800	0,979	302	5,435	14500	295,66	4287041	23297924	8755,5	126954976
	15	CSM	0,33	300	0,625	302	4,632	6950	188,75	1311813	6076971	4056,7	28194272
	16	WR	0,5	800	0,979	302	3,831	14500	295,66	4287041	16421511	4361,7	63245002
	17	CSM	0,33	300	0,625	302	3,028	6950	188,75	1311813	3972824	1737,3	12074400
	18	WR	0,5	800	0,979	302	2,227	14500	295,66	4287041	9545097	1489,3	21594564
	19	CSM	0,33	300	0,625	302	1,424	6950	188,75	1311813	1868677	389,2	2704632
Wet, *see* Note	20	CSM	0,286	450	1,112	302	0,556	6290	335,82	2112333	1174457	138,4	870664
TOTALS					85,305				4436,05	53219882	1194228249		70480944121

NOTE
The crown of the stiffener is considered to be in compression in this example. 'Dry' indicates the face of the stiffener within the hull and 'wet' the outside of the shell laminate, *see* Fig. 4.1.4.

Position of neutral axis above base = $\dfrac{1194228249}{53219882}$ = 22,44 mm above base

Tensile modulus of elasticity of section = $\dfrac{53219882}{4436,05}$ = 11997 N/mm^2

Stiffness EI of section about NA = 4368304 N cm^4/mm^2

1.7 The tabulation considers the entire section and calculates all moments about the base, which is taken to be the outer (wet) surface. The stiffness, EI, of the entire section, about the neutral axis, is determined using the parallel axis theorem:

In general,

$$I_{na} = I_{xx} - Ay^2$$
$$EI_{sect} = \Sigma\, EI_{base} - (\Sigma\, Etb) \times y^2$$

where

y = distance of neutral axis above the base (mm)

From the tabulation:

$$EI_{sect} = 70480944121 - 53219882 \times (22{,}44)^2$$
$$= 4368304336 \text{ Nmm}^4/\text{mm}^2$$
$$EI_{sect} = 4{,}368 \times 10^6 \text{ Ncm}^4/\text{mm}^2$$

From Pt 8, Ch 3,1.15 of the Rules for Special Service Craft the individual layer stresses are determined from:

$$\sigma_{ti} = \frac{E_{ti}\, y_i\, M}{\Sigma\, (E_i\, I_i)} \times 10^{-1} \text{ N/mm}^2$$

The calculation of the stresses in individual layers becomes:

$$\sigma_{ti} = \frac{2917}{4{,}368 \times 10^6} \times E_i\, y_i \times 10^{-1} \text{ N/mm}^2$$

$$\sigma_{ti} = 66{,}8 \times 10^{-6} \times E_i\, y_i \text{ N/mm}^2$$

where

E_i = modulus of elasticity of layer (N/mm²)
y_i = distance of layer from the neutral axis (mm)

The 'top-hat' stiffener is subjected to a load model shown in Fig. 4.1.4. The diagram indicates the areas of tension and compression that exist on either side of the stiffener.

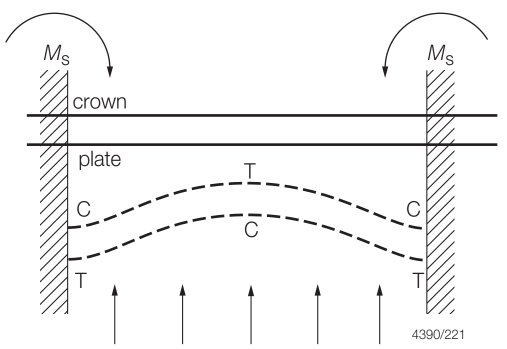

Fig. 4.1.4
Regions of tension (T) and compression (C) in example model

■ *Section 2*
Bending moment at fixed end of stiffener

2.1 The generalised stress equation is:

$$\sigma_i = 66{,}8 \times 10^{-6} \times E_i\, y_i \text{ N/mm}^2$$

The ultimate material properties may be found from Tables 3.1.1 and 3.1.2 in Pt 8, Ch 3 of the Rules for Special Service Craft and the limiting stress fractions from Table 7.3.1 in Pt 8, Ch 3 of the Rules for Special Service Craft.

2.1.1 Consider the crown of the stiffener:

(a) Consider the WR (G_c = 0,5) in compression:

$$E_c = 14000 \text{ N/mm}^2$$
$$y_i = 85{,}305 - 22{,}44$$
$$= 62{,}865 \text{ mm}$$
$$\sigma_{WR\ comp} = 66{,}8 \times 10^{-6} \times 14000 \times 62{,}865$$
$$= 58{,}8 \text{ N/mm}^2$$
$$\sigma_{WR\ ucs} = 147 \text{ N/mm}^2$$

Stress fraction = 58,8/147 = 0,40 hence reject.

(b) Consider the UDT (G_c = 0,54) in compression:

$$E_c = 20748 \text{ N/mm}^2$$
$$y_i = 85{,}305 - 22{,}44 - (2 \times 0{,}979)$$
$$= 60{,}907 \text{ mm}$$
$$\sigma_{UDT\ comp} = 66{,}8 \times 10^{-6} \times 20748 \times 60{,}907$$
$$= 84{,}4 \text{ N/mm}^2$$
$$\sigma_{UDT\ ucs} = 279 \text{ N/mm}^2$$

Stress fraction = 84,4/279 = 0,303 hence acceptable.

(c) Consider the CSM (G_c = 0,33) over the stiffener former in compression:

$$E_c = 7200 \text{ N/mm}^2$$
$$y_i = (85{,}305 - 22{,}44) - (4 \times 0{,}979) - (2 \times 0{,}66)$$
$$= 57{,}629 \text{ mm}$$
$$\sigma_{CSM\ comp} = 66{,}8 \times 10^{-6} \times 7200 \times 57{,}629$$
$$= 27{,}7 \text{ N/mm}^2$$
$$\sigma_{CSM\ ucs} = 122 \text{ N/mm}^2$$

Stress fraction = 27,7/122 = 0,227 hence acceptable.

2.1.2 Consider the loaded face of the shell:

(a) Consider the wet surface CSM (G_c = 0,286) in tension:

$$E_t = 6290 \text{ N/mm}^2$$
$$y_i = 22{,}44 \text{ mm}$$
$$\sigma_{CSM\ tension} = 66{,}8 \times 10^{-6} \times 6290 \times 22{,}44$$
$$= 9{,}4 \text{ N/mm}^2$$
$$\sigma_{CSM\ uts} = 91 \text{ N/mm}^2$$

Stress fraction = 9,4/91 = 0,10 hence acceptable.

Due to such a low stress fraction the adjacent CSM (G_c = 0,33) will also be acceptable.

(b) Consider the WR (G_c = 0,5) in tension:

$$E_t = 14500 \text{ N/mm}^2$$
$$y_i = 22{,}44 - 1{,}112 - 0{,}625$$
$$= 20{,}703 \text{ mm}$$
$$\sigma_{WR\ tension} = 66{,}8 \times 10^{-6} \times 14500 \times 20{,}703$$
$$= 20{,}05 \text{ N/mm}^2$$
$$\sigma_{WR\ uts} = 190 \text{ N/mm}^2$$

Stress fraction = 20,05/190 = 0,105 hence acceptable.

2.2 However, the conclusion is that the compressive stress fraction in the WR in the crown of the stiffener is unacceptable. A number of options exist, which include:

(a) The use of higher strength materials such as carbon fibre or aramid reinforcements.
(b) Add UDT reinforcements in the crown of the stiffener.
(c) Laminate local collars at the end of the stiffeners to increase the section stiffness. This is usually labour intensive and not weight efficient.

2.3 Logically, for this example, the easiest solution is to add UDT reinforcements in the crown of the stiffener. Two additional UDT reinforcements have been included in the revised arrangement. The effect on the section stiffness of the revised schedule is shown in Table 4.2.1.

2.4 Recalculation of stress in the WR reinforcement in the stiffener crown using the revised section stiffness of 5200996 Ncm/mm^2:

$$\sigma_{ti} = \frac{2917}{5200996} \times E_i\, y_i \times 10^{-1} \text{ N/mm}^2$$

$$\sigma_{ti} = 56{,}09 \times 10^{-6} \times E_i\, y_i \text{ N/mm}^2$$

Consider the WR (G_c = 0,5) in the crown of the stiffener in compression:

$$\begin{aligned} E_c &= 14000 \text{ N/mm}^2 \\ y_i &= 86{,}625 - 24{,}926 \\ &= 61{,}7 \text{ mm} \\ \sigma_{WR\ comp} &= 56{,}09 \times 10^{-6} \times 14000 \times 61{,}7 \\ &= 48{,}4 \text{ N/mm}^2 \\ \sigma_{WR\ ucs} &= 147 \text{ N/mm}^2 \end{aligned}$$

Stress fraction = 48,4/147 = 0,329 hence acceptable.

2.5 Re-consider the outermost UDT (G_c = 0,54) in compression:

$$\begin{aligned} E_c &= 20748 \text{ N/mm}^2 \\ y_i &= 86{,}625 - 24{,}926 - 0{,}979 \\ &= 60{,}720 \text{ mm} \\ \sigma_{UDT\ comp} &= 56{,}07 \times 10^{-6} \times 20748 \times 60{,}720 \\ &= 70{,}66 \text{ N/mm}^2 \\ \sigma_{UDT\ ucs} &= 279 \text{ N/mm}^2 \end{aligned}$$

Stress fraction = 70,66/279 = 0,25 hence acceptable.

2.6 The example demonstrates that the additional two UDT's in the crown increases the section stiffness by 19 per cent and is accompanied by a movement in the neutral axis from 22,44 – 24,926 mm above the base. The stress fraction in the woven roving in the crown is reduced from 0,4 to 0,329 and meets the Rule requirement of 0,33.

Considerable care must be exercised when additional material radically affects the position of the neutral axis. For this reason the stress in the outermost UDT's has also been re-calculated and found to be satisfactory.

2.7 Where aramid reinforcements are being used then special consideration must be given to the compressive properties. For comparison purposes aramid reinforcements, at a fibre content of 0,45, typically have the following properties:

	Tension	Compression
Ultimate strength (N/mm^2)	300	100
Elastic modulus (N/mm^2)	21000	17000

2.8 The radical reduction in ultimate compressive strength may prove to be unsuitable in the crown of the stiffener at the end or in the panel at mid span. Designs which feature aramid fibres in the outer plies of the panel, in an attempt to make use of the superior impact properties, must be checked at mid span for compression in the individual layers. This also applies to hybrid reinforcements containing aramid fibres. These reinforcements have one off properties of higher than one of the constituent fibres however, in service the individual allowable strains for each fibre reinforcement should not be exceeded.

2.9 In accordance with Pt 8,Ch 3,1.5.1 of the Rules for Special Service Craft, it is of paramount importance that the strain compatibility of the component materials is carefully considered.

2.10 Consider typical values of apparent strain, ε_a, at failure for the following materials in laminate form:

	Tension	Compression
'E' glass	1,3%	1,05%
Carbon fibre	0,9%	0,55%
Aramid fibre	1,3%	0,60%

2.11 The actual strain permissible is controlled by the material with the lowest apparent strain. The level of strain depends upon whether the reinforcements are in tension or compression and depends on their relative positions within the laminate. Consequently if, for example, a carbon fibre reinforcement is used in the crown of the stiffener then the compression strain must be constrained to a maximum of 0,33 x 0,55 per cent, i.e., 0,297 per cent. Therefore, the corresponding allowable stress in the other reinforcements must be related to the strain in the reinforcement relative to its position away from the neutral axis and that of the carbon fibre reinforcement, e.g.:

$$\varepsilon_{limitWR} = \frac{\varepsilon_{allowable\ carbon} \times y_{WR}}{y_{carbon}}$$

2.12 Other materials incoporated into stiffening members requiring strain compability consideration are plywoods, timbers, etc., which have very differing strains at failure dependent upon the direction of the grain.

Table 4.2.1 **Revised tabulation of 'top-hat' stiffener calculations including additional uni-directional reinforcements**

	Ply No.	Description	G_c	Weight (g/m²)	t (mm)	Breadth, b (mm)	Lever @ base, x (mm)	E (N/mm²)	$t.b$	$E.t.b$	$E.t.b.x$	I @ base	EI @ base
Dry, *see* Note	1	WR	0,5	800	0,979	80	86,136	14000	78,32	1096480	94445853	581087,7	8135228350
	2	UDT	0,54	600	0,660	80	85,316	20748	52,80	1095494	93463200	384323,6	7973946157
	3	WR	0,5	600	0,979	80	84,497	14000	78,32	1096480	92648722	559184,3	7828580341
	4	UDT	0,54	600	0,660	80	83,677	20748	52,80	1095494	91667685	369699,1	7670516637
	5	UDT	0,54	600	0,660	80	83,017	20748	52,80	1095494	90944659	363890,1	7549992490
	6	WR	0,5	800	0,979	80	82,198	14000	78,32	1096480	90127915	529169,8	7408376853
	7	UDT	0,54	600	0,660	80	81,378	20748	52,80	1095494	89149143	349663,5	7254818749
	8	WR	0,5	800	0,979	80	80,559	14000	78,32	1096480	88330784	508277,4	7115883045
	9	CSM	0,33	450	0,937	80	79,601	7200	74,96	539712	42961345	474970,0	3419784035
	10	web	0,5	–	66,850	9,706	45,707	12687	648,85	8231910	376255932	1597160,7	20263177372
	11	bonding	0,5	–	3,150	170,000	10,707	14500	535,50	7764750	83137178	61832,4	896570245
	12	WR	0,5	800	0,979	302	8,643	14500	295,66	4287041	37050752	22107,1	320553529
	13	CSM	0,33	300	0,625	302	7,840	6950	188,75	1311813	10285266	11609,3	80684330
	14	WR	0,5	800	0,979	302	7,039	14500	295,66	4287041	30174338	14670,7	212724485
	15	CSM	0,33	300	0,625	302	6,236	6950	188,75	1311813	8181119	7347,4	51064249
	16	WR	0,5	800	0,979	302	5,435	14500	295,66	4287041	23297924	8755,5	126954976
	17	CSM	0,33	300	0,625	302	4,632	6950	188,75	1311813	6076971	4056,7	28194272
	18	WR	0,5	800	0,979	302	3,831	14500	295,66	4287041	16421511	4361,7	63245002
	19	CSM	0,33	300	0,625	302	3,028	6950	188,75	1311813	3972824	1737,3	12074400
	20	WR	0,5	800	0,979	302	2,227	14500	295,66	4287041	9545097	1489,3	21594564
	21	CSM	0,33	300	0,625	302	1,424	6950	188,75	1311813	1868677	389,2	2704632
Wet, *see* Note	22	CSM	0,286	450	1,112	302	0,556	6290	335,82	2112333	1174457	138,4	870664
TOTALS					86,625				4541,65	55410871	1381181352		86437539378

NOTE: 'Dry' indicates the face of the stiffener within the hull and 'wet' the outside of the shell laminate, *see* Fig. 4.1.4. Consider the crown of the stiffener in compression.

Position of neutral axis above base = $\dfrac{1381181352}{55410871}$ = 24,926 mm above base

Tensile modulus of elasticity of section = $\dfrac{55410871}{4541,65}$ = 12201 N/mm²

Stiffness EI of section about NA = 5200996 N cm⁴/mm²

Section 3
Web thickness to meet shear requirement

3.1 Ultimate shear stress from Table 3.1.2 in Pt 8, Ch 3 of the Rules for Special Service Craft. From the web thickness (4,853 mm) given in 1.5 and the web laminate schedule given in Fig. 4.1.3 (i.e. total weight of 3650 g/m^2) the effective glass content may be calculated, by transforming the relationship given in Pt 8, Ch 4,1.6.1 of the Rules for Special Service Craft. The effective glass content of the web is therefore 0,47.

$$\tau_S = 80\,G_c + 38 = 76 \ \text{N/mm}^2$$

From Pt 8, Ch 7, Table 7.3.1 of the Rules for Special Service Craft.
Limiting shear stress fraction = 0,33
Limiting shear stress = 0,33 x 76 = 25,08 N/mm^2.

3.2 The shear stress requirement is given in Pt 8, Ch 3,1.14.3 of the Rules for Special Service Craft. By setting the shear stress to the limiting shear stress the equation may be rearranged:

$$t_w = F_S/(2 \times d_w \times \tau_S) \ \text{mm}$$

The actual shear load is given in Pt 8, Ch 3,1.14.2 of the Rules for Special Service Craft.

$$F_s = \phi_S\, p\, s\, l_e \ \text{N}$$

The shear stress coefficient is obtained from Table 3.1.5 in Pt 8, Ch 3 of the Rules for Special Service Craft.

$$F_s = 0{,}5 \times 70 \times 500 \times 1 = 17500 \ \text{N}$$

Consequently, the minimum web thickness to meet the Rule requirement is:

$$t_w = 17500/(2 \times 70 \times 25{,}08) = 4{,}98 \ \text{mm}$$

The actual web thickness is 4,853 mm. The deficiency is only 0,127 mm and is considered acceptable.

3.3 Finally, check the minimum Rule requirement for web thickness. From Pt 8, Ch 3,1.16.2 of the Rules for Special Service Craft.

$$t_w = \frac{0{,}025 d_w + 1{,}1}{1{,}3 f_w + 0{,}61}$$

For a web depth of 70 mm and fibre content of 0,47 the minimum web thickness is 2,33 mm. Hence the minimum requirement is fulfilled.

Section 4
Calculation of deflection

4.1 The deflection is calculated from Pt 8, Ch 3,1.14.5 of the Rules for Special Service Craft. From the tabulation the overall section stiffness is $(EI)_S$ = 5200996 Ncm^4/mm^2

$$\delta_s = \frac{\phi_S\, p\, s\, l^4}{(EI)_S} \times 10^5 \ \text{mm}$$

$$\delta_s = \frac{1}{348} \; \frac{70 \times 500 \times 1^4}{5200996} \times 10^5 \ \text{mm}$$

$$\delta_s = 1{,}93 \ \text{mm}.$$

4.2 The limiting span/deflection ratio is given in Table 7.2.1 in Pt 8, Ch 7 of the Rules for Special Service Craft and typically for a bottom longitudinal (not in the slamming zone) the ratio required is 150.

Span/deflection ratio = length/mid-point deflection
= 1000/1,7
= 588 hence acceptable.

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