UNIVERSITY OF Southampton

Modernising composite materials regulations:
Structural approval procedure for marine structures

Lloyd's Register

The purpose is to describe how the structural approval procedure works for marine structures made from polymer composite materials that would generally need to be SOLAS compliant. The flowchart of the procedure and the narrative is from a collaboration between the University of Southampton and Lloyd's Register, to publish a 'discussion document' for feedback and updates as required. Its intention is to highlight the involvement of the key stakeholders in the approval process and indicate potential blockers/bottlenecks and possibilities to streamline the process, or reduce the timescales. Three case studies are included to show specific examples of navigation through different stages of the flowchart.

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Flowchart narrative

Flag administrations regulate on behalf of the **IMO**, for marine structures that are SOLAS compliant or have been assessed as an Alternative Design and Arrangement (AD&A) via Regulation 17 of SOLAS or via a **Classification Society's** requirements. This would be applicable for any structure, including primary load bearing structures, and following this narrative three specific case studies have been considered to show examples of navigation through the structural approval procedures:

1. Repair of corroded ferry decks
2. Design and construction of FPSO (Floating Production Storage and Offloading) installations
3. Pressure vessels

Timescales are project specific, and could be between 2 months for established procedures and 2 years for new concepts that require coupon, sub-scale and full-scale tests (for example). This reflects the technology maturity of the solution, including in-service performance/ experience. Opportunities to speed up the process up are indicated by , and hold points are indicated by .

Stakeholders:

IMO
Flag
Classification Society (e.g. Lloyd's Register)
Shipyard
Designer
Operator

Abbreviations:

AD&A	Alternative Design & Arrangements
AiP	Approval in Principle
ALARP	As Low As Reasonably Practicable
ITP	Inspection and Test Plan
GISIS database	Global Integrated Shipping Information System database
QC	Quality Control
RO	Recognised Organisation
SQEP	Suitably Qualified and Experienced Personnel
TQ	Technology Qualification
TRL	Technology Readiness Level

Stages:

1. Conceptual design

- Requirement specification
- Operational loads
- Design constraints
- Regulatory constraints/framework
- Concepts
- Material selection. Use of approved materials
- Manufacturing process. Approved manufacture processes and/or use of Quality Control (QC) schemes
- Design. Pre-approved designs
- In-service requirements and operational aspects (beyond scope of **Classification Society**)

Type approval may also be applicable

This also includes scope modification and repair proposals. The involvement of a **Classification Society** at the right time can speed up the process, , for example in the marinisation of a technique/procedure/product, so the route to acceptance can be understood and appropriate guidance given.

Demonstrating equivalence[1] can be achieved through a number of routes:

- Re-use of AD&A justification
- Modification of AD&A justification
- SOLAS performance standard
- Existing performance standard
- Enumerating performance standard
- Risk based approach (agree risk criteria with Flag (equivalence orAs Low As Reasonably Practicable (ALARP)[2])

It is also possible to obtain Approval in Principle (AiP) at the concept stage, with appropriate caveats, as an optional step.

2. Design review and appraisal

Equivalent arrangements, including AD&A are the responsibility of the **Flag** States to approve. Having done so the **Flag** then notifies **IMO**, including background information as applicable, and this is published on the **IMO** (Global Integrated Shipping Information System (GISIS) database. These can be general or ship specific.

Classification Society and **Flag** involvement (or not depending on the route taken) depends on the status of the **Classification Society** and whether or not they are delegated by the **Flag** to undertake an assessment for compliance.

Flag: Appraise and approve[1]

Classification Society supports **Shipyard** and **Designer** with achieving a design that complies with rules and statutory requirements. The design is appraised and approved by the **Flag** and notified to **IMO**.

Flag: Approve[1]

A **Classification Society** may also appraise the design as a Recognised Organisation (RO) delegated by the **Flag** and subsequently the **Flag** approves the design and notifies **IMO**.

Design review:

Much of the information/data for structural approval is created in the Design review stage, to be assessed against the **Classification Society** rules and procedures in the Design appraisal and subsequent stages of the approval process.

Technology Qualification (TQ)

- Includes previous marine application or **Classification Society** vessels, prior service history and scope of application. Could allow relaxation of demonstration requirements, and/or inspection periods further in process
- Fabrication process (if novel), and with a description
- Use of internal procedures, or justification of omission. Use of international standards in those procedures, rather than proprietary internal standards will speed the process up **Classification Society** may be able to comment/advise if no specific standards are available

Material qualification

- Use of approved materials
- If materials are not approved then material qualification/approval is required

Manufacturing/fabrication qualification

- Manufacturing QC, including:
  - Inspection procedures/intervals, as defined by Inspection and Test Plan (ITP)
  - Surface preparation and bonding procedures
  - Laboratory scale mock-ups/prototypes (for novel/unproven technology)
- Use of approved workshops or those certified with appropriate QC procedures

Detailed design analysis (for novel/unproven technology)

- May not be required, depending on **Classification Society** rules. Design verification may include 'detailed design analysis' assessed on a case by case basis. Depth of evidence required will depend on the arrangement and its novelty. Approach taken will be project specific and can include installation procedure

Training requirements

- To demonstrate SQEP (Suitably Qualified and Experienced Personnel)
- Project specific, depending on which member of design team is responsible
- Risk based, e.g. translation of requirements and training to installation/modifications by 'riding crews'

3. Demonstration

This also includes the definition of inspection requirements, technique, interval and SQEP of inspection personnel. Polymer composite joining technology is generally less mature than that of metallic materials (which have international standards for welding) and there is less availability of the skilled personnel required. Competency is driven by ISO 9001 requirements, provided by the manufacturer with **Classification Society** verification. Requirements often need to be tailored to the materials and construction, and they may also be different at the demonstration and manufacturing stages. At the demonstration stage a Technology Readiness Level (TRL) assessment can be conducted, typically with a workshop held to define the risks and mitigation measures, depending on the application and technology maturity.

TQ requirements define the level of intervention and by whom, and the level of verification required. If desired **Classification Society** involvement in TQ can speed things up by following their specified TQ process and guidance offered . Otherwise other parties put the information/documentation together and submit for review and comment.

If the acceptance criteria is not met then a variety of modifications can be specified, for reassessment, and/or it is shown that tests need repeating or additional tests are required because the scope of testing was not sufficient. Intervention and by whom depends on the technology.

The approval scope is project specific, e.g. for a deck, vessel or wider application.

4. Approval

The scope of approval is defined earlier in the process, and includes the survey procedure and QC requirements , during manufacture. Full approval consists of:

- Design appraisal against any limitations specified in the regulations
- Surveyor inspection of
  - Material qualification and/or manufacturing
  - Construction
  - Qualification/certification tests

This ensures the correct quality level is achieved and the installation matches the approved plan.

5. Construction/installation

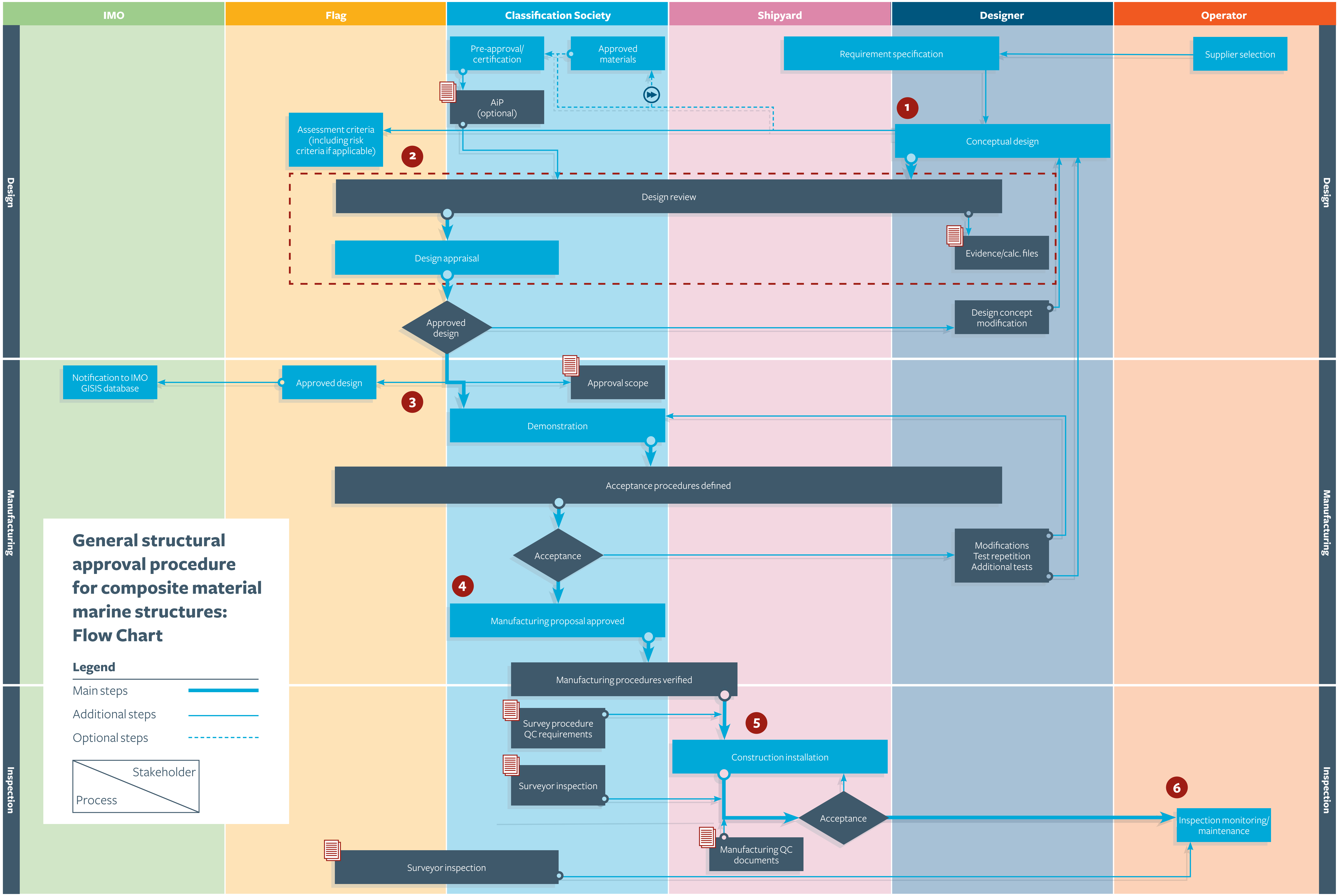
SQEP and competence of manufacturing personnel is defined in Stage 3, via demonstration from laboratory based activity and/or mock-up construction.

Manufacturing QC documentation , will define the relevant quality control and inspection requirements. This may also include testing and survey requirements to validate procedures which have not already been checked at earlier stages.

6. Inspection/monitoring/ maintenance

In-service requirements for inspection/monitoring and maintenance are defined in Stage 3, based on demonstration, and fed into the scope of approval in Stage 4. They are then deployed in-service.

References:
[1] AD&A Flowchart, Lloyd's Register, 05/04/16. High level goal based requirements, rather than equivalence
[2] ShipRight Design and Construction, Additional Design Procedures, Risk Based Designs (RBD), May 2016

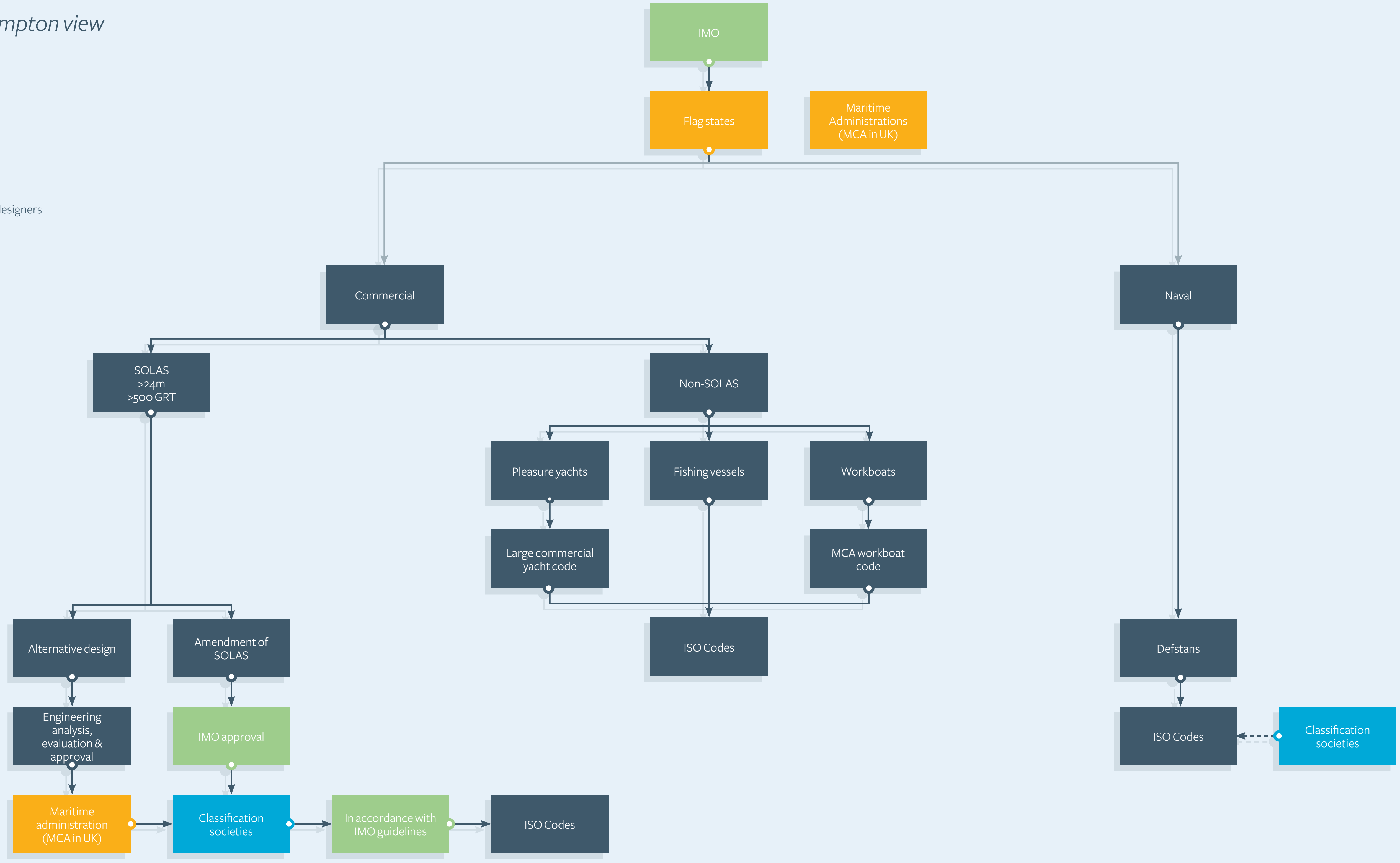

IMO
Flag
Classification Society
Shipyard
Designer
Operator
Design
Manufacturing
Inspection
Pre-approval/ certification
Approved materials
Requirement specification
Supplier selection
AiP (optional)
1
Assessment criteria (including risk criteria if applicable)
2
Conceptual design
Design review
Design appraisal
Evidence/calc. files
Approved design
Design concept modification
Notification to IMO GISIS database
Approved design
Approval scope
3
Demonstration
Acceptance procedures defined
Acceptance
Modifications Test repetition Additional tests
4
Manufacturing proposal approved
Manufacturing procedures verified
Survey procedure QC requirements
5
Construction installation
Surveyor inspection
Acceptance
6
Inspection monitoring/ maintenance
Manufacturing QC documents
Surveyor inspection
General structural approval procedure for composite material marine structures: Flow Chart
Legend
Main steps
Additional steps
Optional steps
Stakeholder
Process

Summary of regulation framework for composite material marine structures Contributors

University of Southampton view

Key

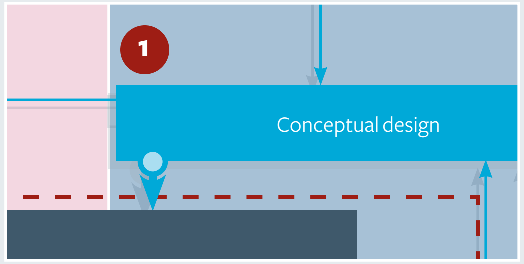
- International requirements
- National regulators
- Regulation flow, operators, designers
- Independent advisors



Case Study 1:
Repair of corroded ferry decks

Once the corrosion of a ferry deck has reached a level required for repair after a survey inspection and the area for repair is within prescribed limits the operator will appoint a company to perform the repair (Supplier selection). The requirement specification is then defined, for a Lloyd's Register classified vessel those covered by Reference[3], when a repair using Sandwich Plate System (SPS) is being considered. SPS is two steel plates bonded to a solid elastomer core. This has advantages over a traditional metallic repair due to there being reduced requirements for gauging and welding, and ability to work from one side, which subsequently reduces the down-time and hence installation cost.

In this case study an overlay repair of a corroded ferry deck has been considered, for which the following items in Table 1 need to be considered in the Conceptual design phase (Stage 1 of the general process/procedure flow chart):



It should be noted that:

1. Designer provides verification of the SPS design
2. Technical support is provided by the manufacturer
3. Lloyd's Register provides guidance for local rule scantling of SPS, guidance on direct calculation, review and comment on the design and analysis and approval of the key drawings

A summary of the full requirements from [3] for other SPS applications is provided in Appendix 1, Table A1.1. A summary of the ship principal dimensions for other applications of sandwich panel construction is given in Table A1.2 of Appendix 1.

In this conceptual design phase (Stage 1 of the general process/procedures flow chart) SPS would constitute the use of an approved material (Type approval), therefore speeding up the approval process. The panel scantling requirements for a deck loaded by wheeled vehicles [3] is as follows:

Table 1: Items to be considered in the Conceptual design phase for an overlay repair [3]

Document	Application	Required item	Additional information
Plan	Overlay (*Note 1*)	Thickness gaugings of the existing structure to be overlaid	Overlay construction is only to be applied when the average gauged thickness after diminution is equal to or greater than 50 per cent of the rule original plate thickness
		Overlay scantlings – core and new steel plate thicknesses	
		Cavity layouts and details	
		Details of integration with the existing structure	For overlay construction attaching the perimeter bars to the existing plating by methods other than welding will be specially considered
		Plans of any proposed modifications and changes to the previously approved plans (of the existing structure)	
		A detailed overlay procedure report	Installation procedure
Design documents	General	Description of how the material components are checked prior to injection and elastomer preparation	(1) Material specifications and tolerances; (2) Listing of materials used; (3) Method and site of manufacture, and suppliers of components; (4) Evidence of selected manufacturer's or sub-contractor's ability to produce the core material in accordance with the design specification (*Note 2*)
	Overlay	A description of the preparation of the existing steel plate	After blasting, incidental cracks or holes are to be repaired to an approved crop/repair procedure

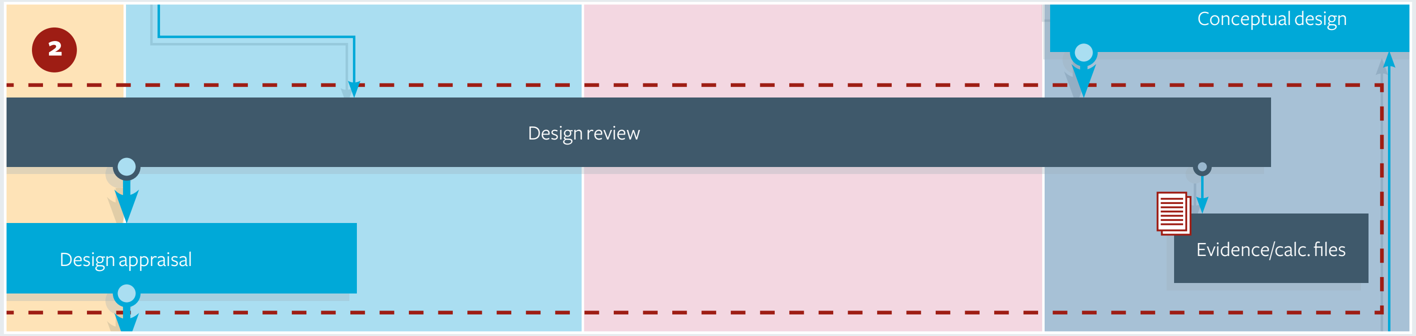
Note 1: It is recommended that the designer discuss the analysis requirements with Lloyd's Register as early as possible in the design cycle

Note 2: This shall be confirmed in each case by an agreed schedule of tests representative of the production being carried out in the presence of an Lloyd's Register surveyor

Table 2: Panel scantling requirements for a deck loaded by wheeled vehicles [3]

Application	Known parameters	Dimensions to be determined	Bending stress
Deck loaded by wheeled vehicles	(1) Thickness allowance (2) Tyre correction factor, n (3) Dynamic magnification factor, λ (4) Load on tyre print (5) Curvature factor coefficients, C1 to C9 (6) Width of the wheel load	(1) Total thickness (2) Thickness of the core (3) Thickness of the top and bottom plate (4) Panel dimensions	$\sigma_b < \sigma_0/k$

The complete summary of panel scantling requirements [1] for other requirements is provided in Table A1.3 in Appendix 1.
At the design appraisal phase (Stage 2), with a deck being a primary load bearing structure the following procedure, for primary support members, needs to be followed [3]:



A. Rule calculation, for primary steel support members not connected to both the bottom and top plating:

a. Reduced thickness of top plating (see Figure 1, which shows Figure 4.3.1 from Reference [3]), to calculate section modulus
b. Calculation according to Rules for Ships [4]
   i. Corrosion margin
   ii. Effective breadth and section moduli
   iii. Hull girder strength
   iv. Decks
   v. Decks loaded by wheeled vehicles
   vi. Superstructure
   vii. Double bottom
   viii. Shell envelope: slamming requirement for structure below waterline; flare slamming

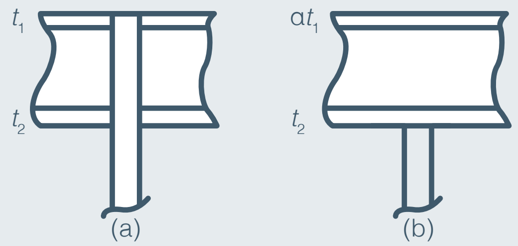
B. Direct calculation

a. ShipRight Structural Design Assessment Procedure [5]
b. Modelling of a sandwich panel
   i. Recommended mesh size for core material and face plate (as α ratio limit)
   ii. Shell for top and bottom plates; solid or shell for core (nodal location)

C. Buckling

a. Elastic critical buckling stress of web plating
b. Refer to Rules for Ships [4]

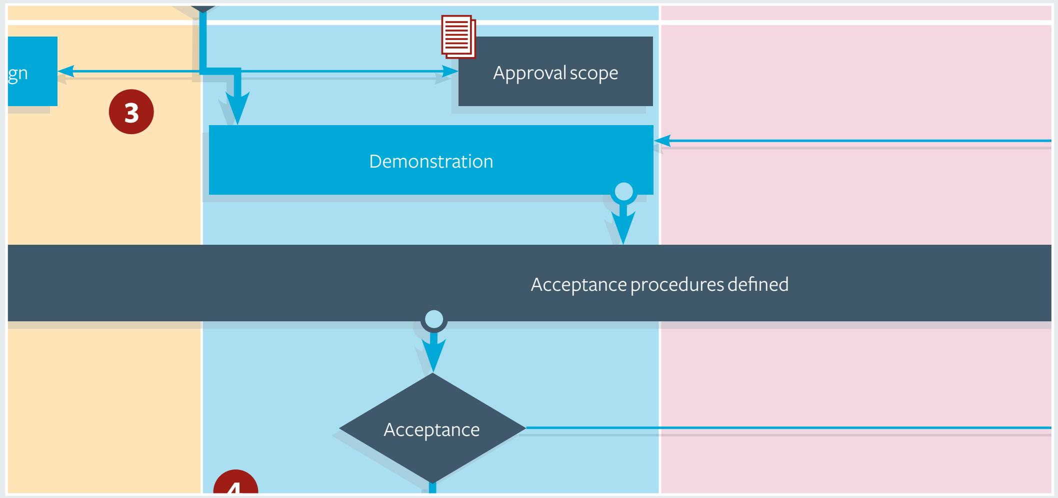
Figure 1: Top plate thickness reduction (for illustration only) [3]



This provides the evidence required at this stage of the process. In other situations of sandwich panel construction Finite Element Analysis (FEA) is required, as summarised in Table A1.4 of Appendix 1. As SPS repair material has become more established calculation procedures have replaced the need for detailed FEA.

As a Type Approved material the approval scope is for a variety of applications, not just repair of a corroded ferry decks, and covers the following elements:

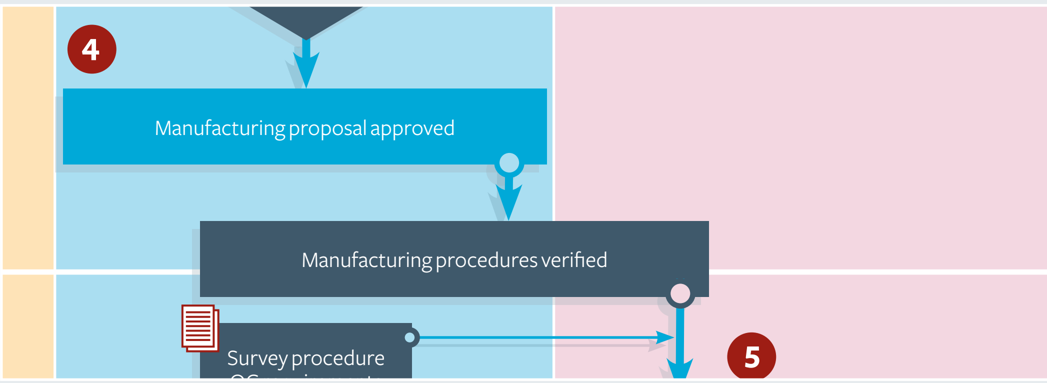
- Technology qualification
- Material qualification
- Manufacturing qualification
- Detailed design analysis
- Training requirements



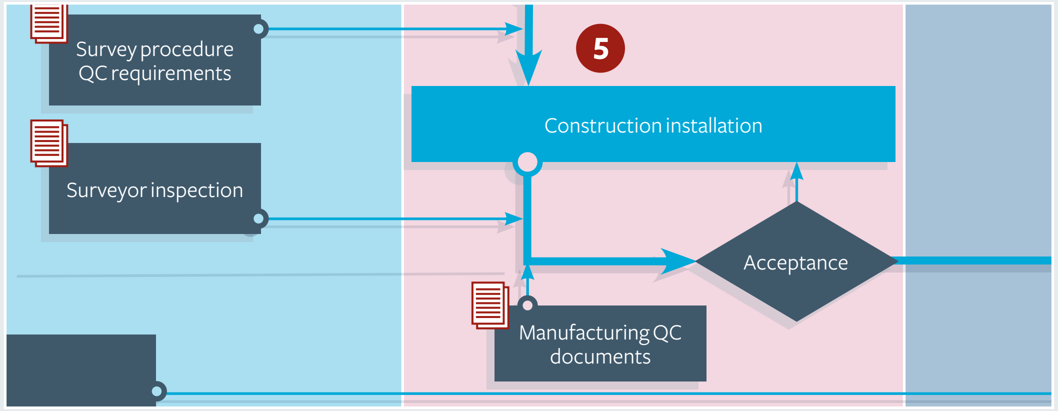
The designer continues to work with the **Shipyard** and **Classification Society** (Lloyd's Register in this case) in the demonstration phase (Stage 3). For a type approved product the shipyard/ builder must verify the material properties for the batch of material to be used in the repair, as summarised in Table 3 below:

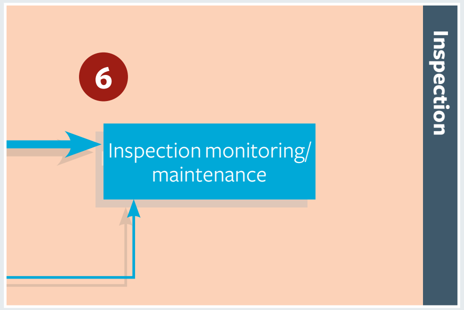
Table 3: Material and manufacturing for sandwich panel construction [3]

Responsibility/ stakeholder	Major item	Item No.	Required item
Builder	Perimeter bars	1	Perimeter bars are to comply with the requirements of Table 2.2.1 Material classes and grades in Pt 3, Ch 2 Materials of the Rules for Ships for secondary structures
Builder	Core material (*Note 1*)	2	Builder to test elastomer desnity, hardness, shear modulus, tensile stress, tensile strain to failure and bond shear strength; to ensure that the material base component's batch test certificates meet the requirements
Builder to obtain Lloyd's Register certification		3	The base component manufacturer must hold valid Lloyd's Register certification
Manufacturer		4	Manufacturer to test Polyol (viscosity, moisture and hydroxyl) and Iso-cyanate (viscosity and iso-cyanate value)
Builder		5	The mixing of the base components and the injection of the mix to form the elastomer is to be carried out according to a written procedure approved by Lloyd's Register
Manufacturer	Panel manufacturing	6	A valid certificate of calibration confirming the accuracy of the pumping equipment
Note 1: If the Surveyor has any cause for concern over the tests listed in this section or the batch properties, he may at any time, require samples of both elastomer and adhesion to steel samples to be prepared and tested			



This includes the perimeter bars and core materials, for which the manufacturer (shipyard/builder) must have valid Lloyd's Register certification and adhere to their written procedures and SQEP requirements. A Lloyd's Register surveyor will (usually) witness the manufacture/testing of the material. On acceptable completion the approval proposal can be deemed acceptable (Stage 4) and the construction/installation phase (Stage 5) can begin.





Manufacturing QC documents defined in the demonstration phase (Stage 3) are used in the construction/installation phase, in addition to the survey requirements (Stage 5). When the ferry returns to service it will be subjected to the appropriate inspection/monitoring and maintenance requirements (Stage 6) defined in the demonstration phase (Stage 3) and the SQEP requirements.

References:
[3] Provisional Rules for The Application of Sandwich Panel Construction to Ship Structure, Lloyd's Register, July 2015, https://www.lr.org/en-gb/rules-for-the-application-of-sandwich-panel-construction-to-ship-structure/4
[4] Rules and Regulations for the Classification of Ships, July 2018, https://www.lr.org/en-gb/rules-and-regulations-for-the-classification-of-ships/
[5] Lloyd's Register ShipRight procedures, www.lr.org/en/shipright-procedures/

Appendix 1: Additional information for Sandwich Panel Construction to Ship Structure, in accordance with Lloyd's Register Rules [3]

Table A1.1: Items to be considered in the Conceptual design phase

Document	Application	No.	Required item	Additional information
Plan	General	1	All plating thickness	
		2	Stiffener sizes and spacings	
		3	Bracket arrangements and connections	
		4	Corrosion margin or Owner's extra	
		5	Welding, constructional arrangements and tolerances	In areas subject to high stress, deep penetration or full penetration welding may be required
		6	Drawings with the sandwich panel specifications (thickness of top, bottom plating and core thickness)	Closed form formulas
		7	When Sandwich construction has been utilised partly, the exact extent and location are to be indicated on all relevant plans	
		8	Cavity layouts and details	
		9	Details of integration with conventional steel construction, if applicable	
		10	Details of integration with primary members, bulkheads, etc.	
		11	Construction procedure report	After elastomer has cured, the holes for high temperature pressure relief valves are to be drilled
		12	The arrangement of equipments, supports, foundations, etc. in conjunction with their weight and working load information	
	Overlay (*Note 1*)	13	Thickness gaugings of the existing structure to be overlaid	Overlay construction is only to be applied when the average gauged thickness after diminution is equal to or greater than 50 per cent of the rule original plate thickness
		14	Overlay scantlings – core and new steel plate thicknesses	
		15	Cavity layouts and details	
		16	Details of integration with the existing structure	For overlay construction attaching the perimeter bars to the existing plating by methods other than welding will be specially considered
		17	Plans of any proposed modifications and changes to the previously approved plans (of the existing structure)	
		18	A detailed overlay procedure report	Installation procedure
Supporting document		19	Temperature control pressure relief plugs, where fitted – size, number and location	
Design documents	General	20	Detailed description of the preparation of steel	
		21	Description of surface roughness to be achieved	
		22	Description of the arrangement of spacers and perimeter bars	
		23	Description of the panel restraint and arrangement	
		24	Description of how the material components are checked prior to injection and elastomer preparation	(1) Material specifications and tolerances; (2) Listing of materials used; (3) Method and site of manufacture, and suppliers of components; (4) Evidence of selected manufacturer's or sub-contractor's ability to produce the core material in accordance with the design specification (*Note 2*)
		25	Machinery set-up and calibration procedure	
		26	Description of the cavity preparation and injection process	Define locations of venting and injection holes
		27	A description of how the effects of weld heat input will be avoided	
		28	Description of the cavity humidity detection process and method	
		29	Max void size	
		30	A description of the repair process	Modification to procedure needs prior agreement of the Surveyor
	Overlay	31	A description of the preparation of the existing steel plate	After blasting, incidental cracks or holes are to be repaired to an approved crop/repair procedure
Direct calculation	Ships having novel design features or alternative arrangements and scantlings	32	A description of the structural modelling (FEA)	
		33	A summary of analysis parameters including properties and boundary conditions	
		34	Details of the loading conditions and the means of applying loads	
		35	A comprehensive summary of calculation results. Sample calculations should be submitted where appropriate	Comparison with allowable stresses (hull plating components and combined global and local loads) and local deflection limit

Note 1: It is recommended that the designer discuss the analysis requirements with Lloyd's Register as early as possible in the design cycle

Note 2: This shall be confirmed in each case by an agreed schedule of tests representative of the production being carried out in the presence of an Lloyd's Register surveyor

Table A1.2: Ship principal dimensions for sandwich panel construction cases [4]

No.	Type "C" chemical tanker (new construction)	Bulk carrier (new construction)	Cargo vessel strengthening to Ice Class 1D (overlay)
1	Moulded breadth	Moulded breadth	Moulded breadth
2	Moulded depth	Moulded depth	Moulded breadth
3	LOA	LOA	LOA
4	LPP	LPP	LPP
5	Rule length	Rule length	Draught
6	Draught	Draught	Displacement
7	Each cargo tank length	Each cargo tank length	Engine output
8	Gravity of cargo	Cb	
9	Additional pressure (pressure relief value setting)	Design speed	
10	Hydrostatic pressure		
11	Test pressure for main deck		
12	Design pressure for outer side shell and bottom plating		

Abbreviations

CSR	Common Structural Rules
FEA	Finite Element Analysis
IIW	International Institute of Welding
QC	Quality Control
SN	Stress Cycle
SPS	Sandwich Plate System
SQEP	Suitably Qualified and Experienced Personnel

Symbol	Description
b	Breadth of the panel at shortest edge
k	Material factor, ratio of 235 MPa to elastic critical buckling stress
q	Stress of the bulkhead
R	Strength index
s	Spacing of longitudinals
n	Tyre correction factor
q_u	Ultimate bending capacity
t_c	Core thickness
t_{n1}	Net thickness of the top plate
t_{n2}	Net thickness of the bottom plate
β	Coefficient related to the aspect ratio of the panel
γ	Coefficient related to the aspect ratio of the panel
η	Coefficient, 1.5
λ	Dynamic magnification factor
σ_0	Specified minimum yield stress of the face plates
σ_b	Bending stress
σ_c	Elastic critical buckling stress
σ_d	Design compressive stress
σ_E	Critical compressive buckling stress
τ_c	6 MPa

Table A1.3: Panel scantling requirements for sandwich panel construction cases [3]

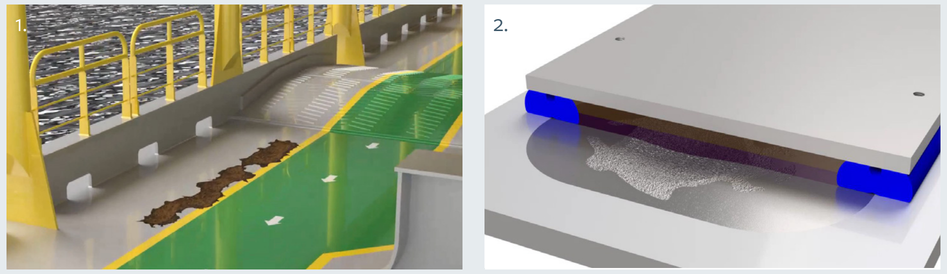
Application	Known parameters	Dimensions to be determined	Minimum thickness	Bond shear capacity	Ultimate bending capacity	Bending stress	Strength Index	Critical buckling stress (elastic)
Watertight bulkheads	(1) Minimum yield stress of the face plate (2) Thickness allowance (3) τ_c (4) η	(1) Total thickness (2) Thickness of the core (3) Thickness of the top and bottom plate (4) Panel dimensions	(1) Core thickness (2) Net thickness of the top and bottom plate	$t_c + t_{n1} + t_{n2} \geq \frac{\beta \, \gamma \, qb}{\tau_c}$	$q_u \geq \eta \, q$			
Deep tank bulkheads	(1) Minimum yield stress of the face plate (2) Corrosion allowance (3) Relative density of liquid carried in a tank (4) τ_c (5) η	(1) Total thickness (2) Thickness of the core (3) Thickness of the top and bottom plate (4) Panel dimensions	(1) Core thickness (2) Net thickness of the top and bottom plate	$t_c + t_{n1} + t_{n2} \geq \frac{\beta \, \gamma \, qb}{\tau_c}$	$q_u \geq \eta \, q$			
Deck loaded by wheeled vehicles	(1) Thickness allowance (2) Tyre correction factor, n (3) Dynamic magnification factor, λ (4) Load on tyre print (5) Curvature factor coefficients, C1 to C9 (6) Width of the wheel load	(1) Total thickness (2) Thickness of the core (3) Thickness of the top and bottom plate (4) Panel dimensions				$\sigma_b < \sigma_0/k$		
Others	(1) Rule thickness allowance (2) Top and bottom plate thickness allowance (3) Equivalent scantlings trule and Zrule (of secondary members) according to Rules for Ships (4) Spacing, s = 700 mm (5) Material factor, k = 1	(1) Thickness of the core (2) Thickness of the top and bottom plate	(1) Core thickness (2) Net thickness of the top and bottom plate				$R \leq 1$	
Overlay scantlings	(1) Equivalent scantlings trule (2) Spacing of longitudinals, s (3) Top plate thickness allowance	(1) Thickness of the core (2) Thickness of the top and bottom plate	(1) Core thickness (2) Net thickness of the top and bottom plate				$R \leq 1$	
Panels subject to in-plane uniaxial compressive stresses	(1) Corrosion margin or Owner's extra is to be deducted (net scantling) (2) Poisson's ratio (3) Minimum design shear modulus of core material, as shown on approval certificate (4) Design compressive stress, σ_d (5) Flexural rigidity of the sandwich	(1) Thickness of the core (2) Thickness of the top and bottom plate						$\sigma_c = \sigma_E$ when $\sigma_E \leq 0.5\,\sigma_0$ $\sigma_c = \sigma_0\left(1 - \frac{\sigma_0}{4\,\sigma_E}\right)$ when $\sigma_E > 0.5\,\sigma_0$ $\frac{\sigma_c}{\sigma_d} \geq 1.1$

Table A1.4: FEA required for other SPS sandwich panel application cases

	Type "C" chemical tanker (new construction)	Bulk carrier (new construction)	Cargo vessel strengthening to Ice Class 1D (overlay)
Application	SPS cargo tank	(1) SPS inner bottom (2) SPS side shell	SPS overlay of external shell plating in ice belt
Model	One cargo tank (half)	Three cargo hold (full)	Local side shell and web frames
Scantling	Net scantling	Net scantling	Net scantling
Element	Layered shell element (elastic-plastic for steel and elastic for core)	(1) Layered shell element (elastic-plastic for steel and elastic for core) (2) Bar element for stiffeners	(1) Layered shell element (elastic-plastic for steel and elastic for core) (2) Thick shell element (solid-shell)
Load condition	(1) Tank test (2) Operation (100% tank filling, pressure valve and maximum hull girder bending: hog and sag)	(1) Homogeneous loading (2) Alternative loading (3) Normal ballast (4) Heavy ballast	Design ice pressure (closed form formula)
Hull girder bending moment	Hull girder bending moments (hogging and sagging) were based on Rule calculation	Hull girder bending moments (hogging and sagging) were based on Rule calculation	
Output	(1) Out-of-plane deflection (2) Comparison with conventional steels (3) Maximum bending and average shear stresses (4) Norminal, longitudinal and von Mises	(1) Out-of-plane deflection (2) Three components of stress tensor of the core (3) Norminal, longitudinal and von Mises	(1) Out-of-plane deflection (2) Comparison with conventional steels (3) Maximum interface shear stresses (4) Norminal, longitudinal and von Mises
Fatigue FEA		(1) SPS welding connections (2) Design life (3) Solid elements (4) Hot spot stress (5) CSR and IIW SN curves (6) Modification of connection design based on fatigue life	

Case Study 2:
Repair of Floating Production Storage and Offloading (FPSO)installations

In this case study two different FPSO repairs, for corroded brackets and the main deck have been considered, the details of which are related to the different stages of the general process/procedure structural approval flow chart below. Once the corrosion has reached a diminution level requiring repair and the area for repair is within prescribed limits the owner/operator will appoint a company to perform the repair (Supplier selection). Background information is included in Appendix 2, and the ColdShieldTM technology (see Figure 2) has been used to repair these primary structural FPSO members.



1. Corroded deck
2. Cut-away of reinforcement pad over prepared surface
3. Reinforcement pad positioned over repair area
4. Completed repair
5. Repair configuration

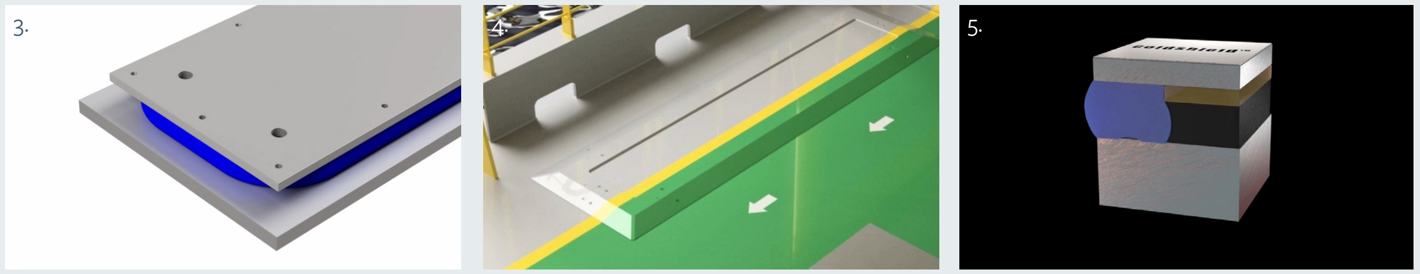


Figure 2: Cold Pad deck repair configuration [6] (Courtesy of Cold Pad)

ColdShield™ is a product developed by Coldpad, through a collaboration between ifp Energies nouvelles and Total, and approved by the following Classification Societies: ABS, Bureau Veritas, DNV·GL and Lloyd's Register, **www.cold-pad.com/coldshield**.

2.1 Bracket repair

Four brackets in a void located close to two crude oil tanks were identified by the **Classification Society**, ABS, that required repair on a permanently moored FPSO in deep-water off the coast of West Africa [7], see Figure 3. A three party project team, comprising the FPSO operation team from Total, Cold Pad, and SBM Offshore was formed to perform the repairs, which were performed over the course of three days, utilising 16 person days offshore, which was a significant reduction to a hot work, welded, solution (which would take 15 days and thus saved 3M USD), and minimised health and safety risks in an explosive environment.

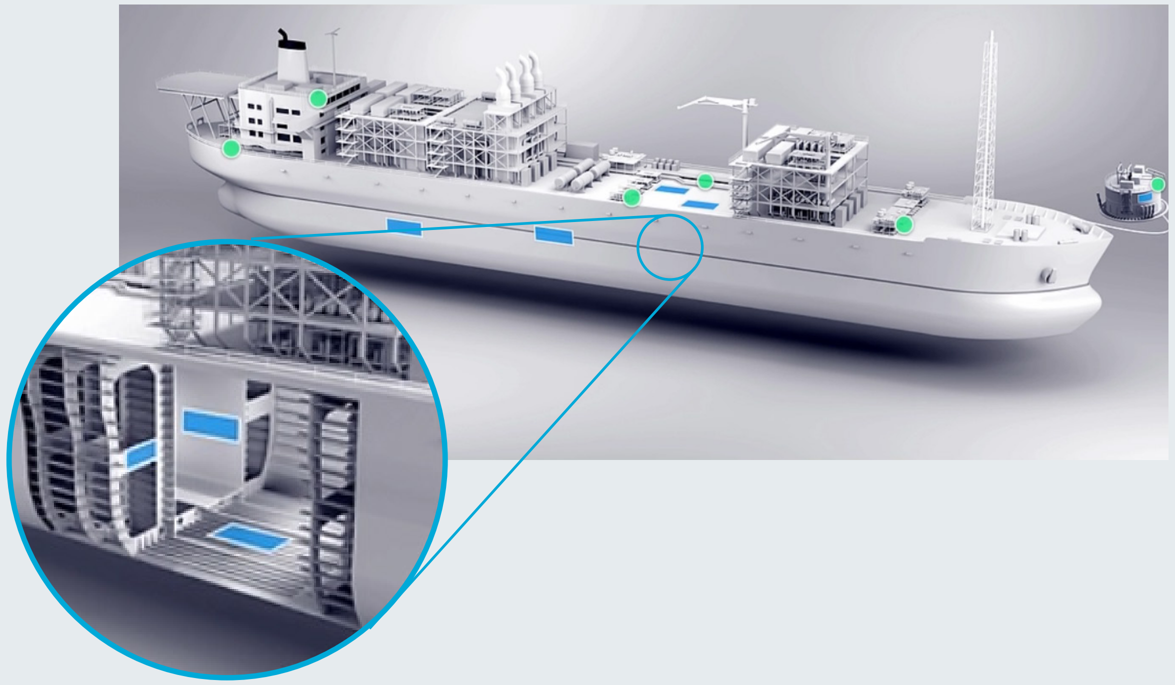
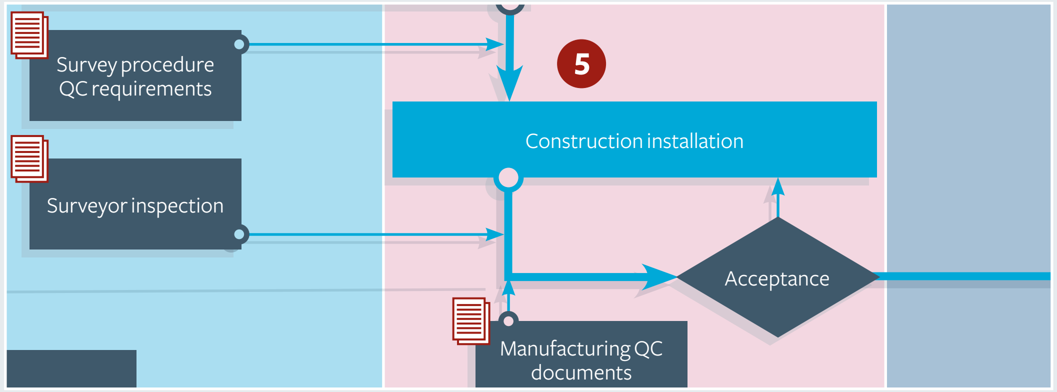


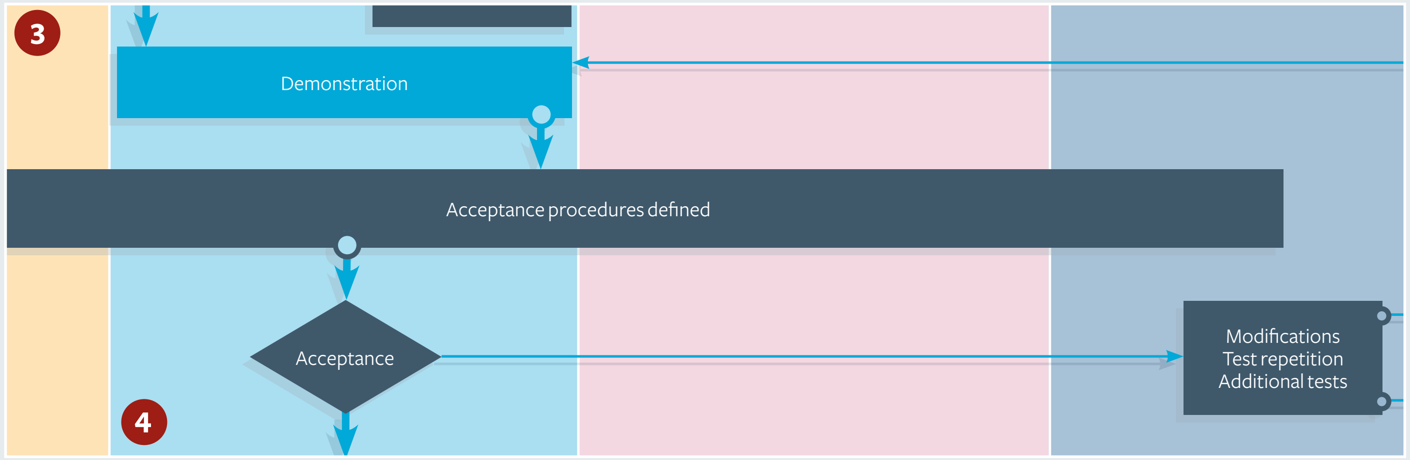
Figure 3: Corroded brackets located close to two crude oil tanks[6] (Courtesy of Cold Pad)

During the Construction/installation phase (Stage 5 of the general process/procedure flow chart) the key stages were as follows:



Surface preparation was performed to the same specifications as the Total procedures for offshore painting. The reinforcement pad (super duplex plate and compressed fluorosilicone seal) is pre-fabricated in a factory, to be bonded to the damaged structure using a structural epoxy adhesive. The reinforcement pad was positioned on the corroded area and a peripheral seal used to pilot and monitor the adhesive injection steps, before curing. The seal allows an industrial vacuum to be pulled between the reinforcement and base material, and most importantly the dehydration of the internal volume to below 1% relative humidity. The low modulus polymer of the intermediate deformation layer (see Figure 2) reduces the stress intensity significantly at the extremities of the repair and minimises edge effects. The repairs were then surveyed, including acoustic tap tests to verify the absence of voids, and approved by ABS, the **Classification Society**.

The durability of the ColdShield™ technology was demonstrated in a three year long research and development programme by ifp Energies nouvelles, Total, and Bureau Veritas, in the Demonstration phase (Stage 3):



This was via accelerated aging tests to demonstrated resistance to thermal and mechanical aging (mechanical and thermal fatigue and relaxation) and the conclusions of the different full-scale tests and long-term extrapolations from the qualifying campaign were that the **Classification Society**, Bureau Veritas, approved design life of 10 years could be extended with relevant inspection.

The development and demonstration work built on existing 'classical' bonded composite solutions from the European FP7 Co-Patch project to qualify and certify a new solution via a combination of small-scale and full-scale testing and numerical analysis. The small scale tests included single-lap shear tests to optimise the repair patch parameters such as the reinforcement and structural epoxy thickness, the chamfer characteristics and the shape of the intermediate deformation layer. The numerical analysis was used to analyse the stresses at the bondline and demonstrate confidence in the robustness of a stress-based prediction criteria.

2.2 Main Deck repair

The hull of an FPSO with a production capacity of 240,000 barrels per day suffered from localised corrosion of the main deck [9], due to coating failure/damage, see Figure 4. The corrosion was greater than the acceptance criteria set by the IACS (International Association of Classification Societies) and thus the **Classification Society**, Bureau Veritas issued a recommendation to repair. The **Operator**, Total, considered different repair options, of which the ColdShield™ was considered the only viable option with the requirement to minimise the both the production and safety impacts, which discounted hot work on top of hydrocarbon tanks. The structural repair maintenance was done during normal operation, rather than during a planned shutdown, saving 140 offshore person days for the 10 m² that required repair, see Figure 5, and tens of millions of USD.

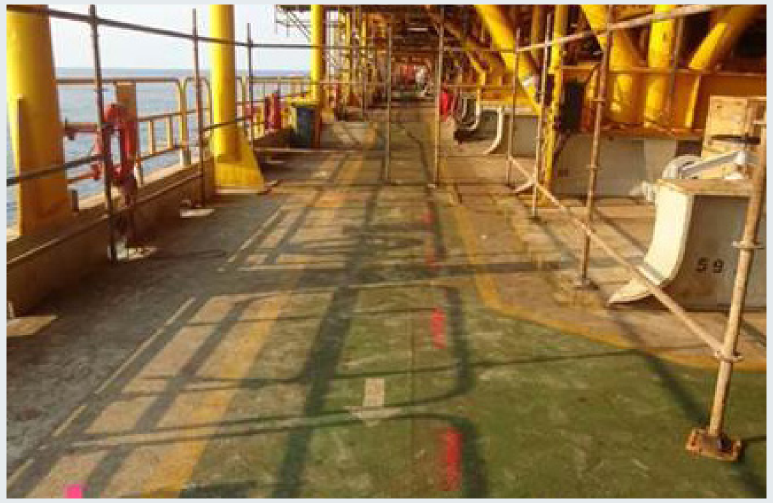


Figure 4: Corroded deck plating of an FPSO (Courtesy of Cold Pad)

Figure 5: Cold Pad applied to repair the corroded deck (Courtesy of Cold Pad)

Abbreviations

FPSO	Floating Production Storage and Offloading
IACS	International Association of Classification Societies
USD	US Dollars

Appendix 2:
Background information for composite structural repairs of FPSO's

An increasing number of FPSOs have been in service for more than 10 years and maintenance for material deteriorations such as corrosion is routinely carried out. FPSO hulls are normally maintained 'on site', which inevitably poses challenges in terms of safety, reliability and economics.

Conventional repair often involves hot work, which presents major risks for the assets and personnel onboard an explosive environments such as an FPSO. If such repair is to be carried out on a corroded deck plating on top of a crude oil tank, it may take around 15 days to empty the tank, clean it and set up scaffolding [6]. Given the limited number of people working on an FPSO (typically 80 to 150), this means that a wide number of tasks need to be performed by each person within a limited amount of time.

Cold work solutions, often called composite repair, therefore become a potential alternative for asset owners, **Operators** and **Classification Societies**. Without welding, bolting or riveting, this type of repair enables more uniform stress distribution, increased fatigue life, and weight reduction. The quality of the repair highly depends on the adhesive bonding. For structural reinforcement of primary structures in FPSO, the **Classification Society** requires the demonstration of the reliability of the adhesive bonding. A classical bonded reinforcement can be affected by a wide range of factors (Figure A2.1), which can lead to difficulties in defining or predicting the failure mode of a particular bonded assembly design. The bondline strength is governed by shear and normal (peel) stresses [9]. Reduction in one will cause an increase in the other. Good practice in design is to completely release the normal stress of the bonded joint. However, such a constraint may not be easily achieved on load bearing component, especially primary structural members of the hull. In aeronautics, automotive and rail industry, bonding is a "special process" and its quality cannot be fully checked by NDT after manufacturing. To check the installation, DIN 6701-4 [10] and NI 613 [11] suggest quality control and monitoring at all process stages from design to bonding curing [7].

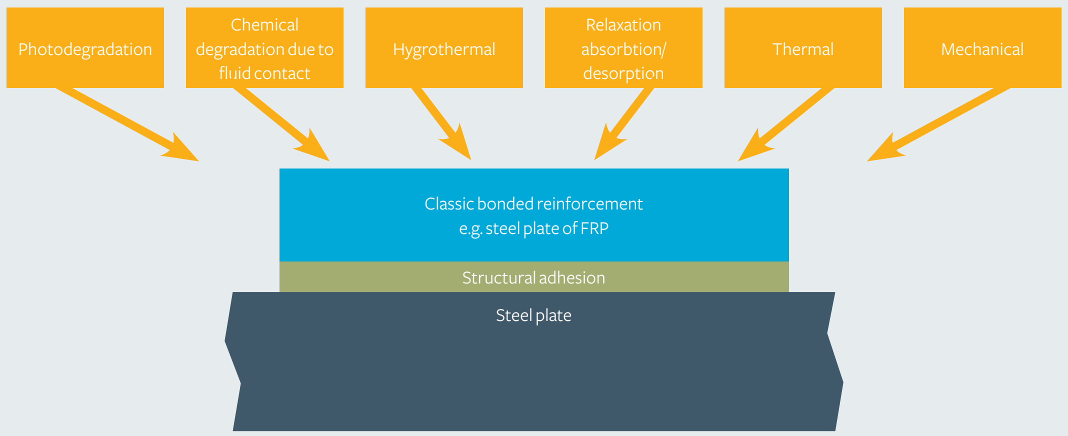


Figure A2.1: Ageing mechanisms for a classical bonded reinforcement [7]

References:

[6] Florio, V., De Beer, T., Errotabehere, X., Paillusseau, C., "FPSO Hull brackets repair by cold bonded reinforcements", Proc. MCE Deep Water Development, Milan, Italy, 2018.

[7] Paillusseau, C., Errotabehere, X., Sayed-Ahamd, F., Mouton, L., "Gamechanging structural repair solution for FPSO hulls with no hot work", Society of Petroleum Engineers, SPE-190897-MS, 2018.

[8] Luila E., Court, J.P., "Girassol FPSO Hull deck repair by bonded reinforcements", Proc. MCE Deep Water Development, Amsterdam, Netherlands, 2017.

[9] Cognard, J.Y., Davies, P., Gineste, B., Sohier, L., "Development of an improved adhesive test method for composite assembly design", Composites Science and Technology, 65 (3-4):359-368, 2005.

[10] DIN 6701-4, Adhesive bonding of railway vehicles and parts - Part 4: Manufacturing controls and quality assurance, 2015, https://global.ihs.com/doc_detail.cfm?document_name=DIN%206701%2D4&item_s_key=00632765

[11] Guidance Note NI 613 DT R00 E, Adhesive joints and patch repair, Bureau Veritas, 2015, https://marine-offshore.bureauveritas.com/sites/g/files/zypfnx136/files/pdf/613-NI_2015-05.pdf

Case Study 3: Composite pressure vessel

This case study presents extracts of the Design Appraisal Document (DAD) that Lloyd's Register issued to the designer (who can also be the yard/builder) for a carbon fibre reinforced composite pressure vessel for Compressed Natural Gas (CNG) storage. The pressure vessel is 40 feet long, with a diameter of 42 inches that marinised a road transport application. The carbon fibre reinforcement (1.13 inches thick) was filament wound over a 0.5 inch thick thermoplastic liner. The requirement specification, typical design operating criteria, was as summarised in Table 4.

Table 4: Typical design operating criteria for a carbon fibre reinforced composite pressure vessel for CNG storage

Pressure/Temperature	Design values
Operating pressure at 15 °C (59 °F)	250 bar
Max filling pressure	325 bar
Test pressure	375 bar
Minimum burst test pressure	> 500 bar
Operating temperature limits	-40 °C to 65 °C
Peak fill and discharge gas temperature	-40 °C to 82 °C

At the Conceptual design phase (Stage 1 of the general process/procedure flow chart) the design codes and standards in Table 5 were examined:

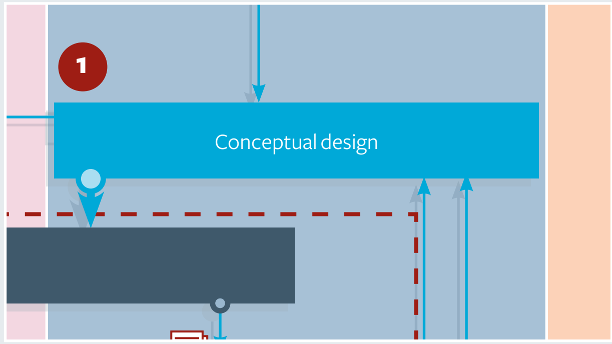
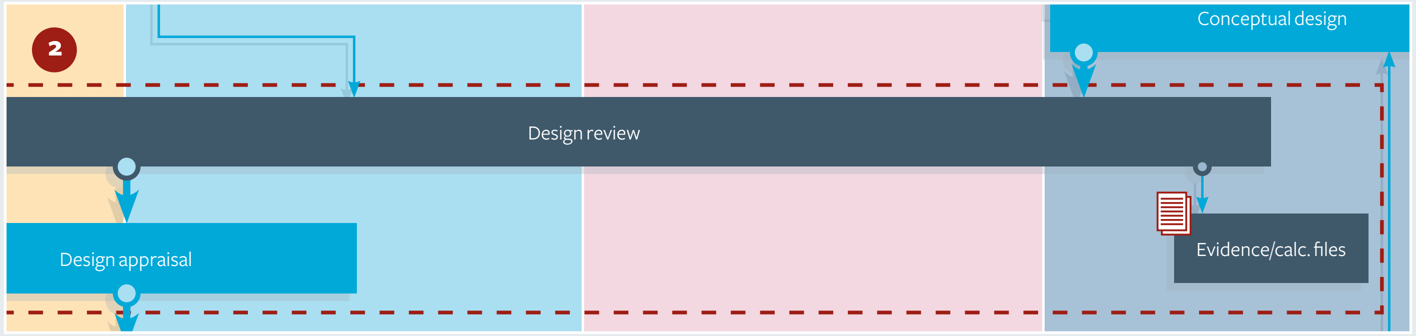


Table 5: Items to be considered in the Conceptual design phase for a carbon fibre reinforced composite pressure vessel for CNG storage

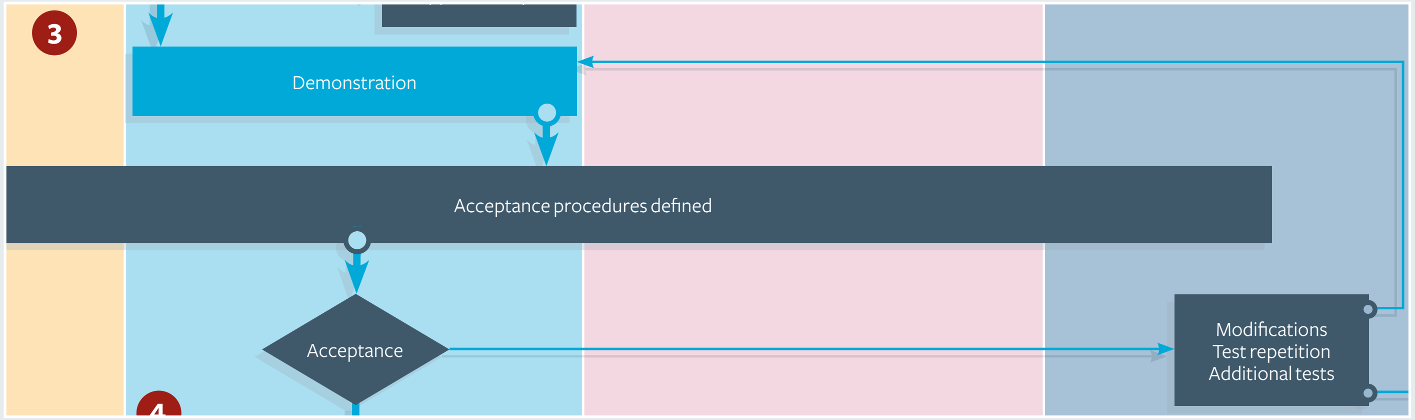
Design Code/Standard	Title	Reference
Lloyd's Register Ship Rules	The general rules requirements of the Lloyd's Register Ship Rules Part 5 Chapter 11, and in accordance with the IMO's International Gas Code (IGC)	[12]
IMO's International Gas Code (IGC)	The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)	[13]
ISO 11119-3: 2013	Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450L with non-load-sharing metallic or non-metallic liners	[14]
PVE/3/3	Transportable Gas Containers - Cylinder Design, Construction and Testing at the Time of Manufacture (bsi Standards Development)	[15]
BS EN 13923: 2005	Filament-wound FRP pressure vessels	[16]
ISO 1496-3: 1995 (2018 Draft)	Series 1 freight containers - Specification and testing - Part 3: Tank containers for liquids, gases and pressurized dry bulk. Version applicable at time of appraisal, 2019 version now available	[17]
ISO 1496-5: 1991 (2017 Draft)	Series 1 freight containers - Specification and testing - Part 5: Platform and platform-based containers. Version applicable at time of appraisal, 2018 version now available	[18]
CGA TB-25	CGA TB-25: Design Considerations for Tube Trailers (USA legal requirement)	[19]
Lloyd's Register ShipRight procedures	Lloyd's Register ShipRight procedures, Design and Construction, Additional Design Procedures, Risk Based Design (RBD)	[20]
IMO MSC.1/Circ.1212	Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III	[21]
IMO MSC.1/Circ.1455	Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments	[22]

During the Design review phase (Stage 2 of the general process/procedure flow chart) a risk analysis report was written and non-linear FEA was used to validate the pressure vessel design:



The risk analysis report considered Failure Mode and Effects Analysis (FMEA), criticality analysis and hazard analysis, including both hardware failure and operator error in addition to the structural aspects.

Materials and component tests were conducted in the Demonstration phase (Stage 3 of the general process/procedure flow chart):



This included the material coupon tests on Toray T700 24K carbon fibre and epoxy specimens required for them to be accepted by Lloyd's Register in accordance with, primarily, US Department of Transport requirements. A burst pressure test was also carried out in accordance with [23] and [24] and the composite pressure vessel was tested to three times its design life in accordance with [14] and [23]. Following design review and mechanical performance verification, the pressure vessel design was accepted (Stage 4) and installed (Stage 5) on a commercial vessel that is currently in-service where it will be subjected to inspection/monitoring as defined earlier in the process/procedure during Stage 6.

Abbreviations

CNG	Compressed Natural Gas
DAD	Design Approval Document
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
IGC	International Gas Code
RBD	Risk Based Design

References:

[12] Rules and Regulations for the Classification of Ships, July 2018, www.lr.org/en/rules-and-regulations-for-the-classification-of-ships/

[13] The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), www.imo.org/en/ourwork/safety/cargoes/cargoesinbulk/pages/igc-code.aspx

[14] ISO 11119-3: 2013, Gas cylinders - Refillable composite gas cylinders and tubes - Design, construction and testing - Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450L with non-load-sharing metallic or non-metallic liners, www.iso.org/standard/50523.html

[15] PVE/3/3 - Transportable Gas Containers - Cylinder Design, Construction and Testing at the Time of Manufacture, bsi Standards Development, https://standardsdevelopment.bsigroup.com/committees/50002657

[16] BS EN 13923: 2005, Filament-wound FRP pressure vessels. Materials, design, manufacturing and testing, https://shop.bsigroup.com/ProductDetail/?pid=000000000030040465

[17] ISO 1496-3: 1995, Series 1 freight containers - Specification and testing - Part 3: Tank containers for liquids, gases and pressurized dry bulk, www.iso.org/standard/3047.html

[18] ISO 1496-5: 1991, Series 1 freight containers - Specification and testing - Part 5: Platform and platform-based containers, www.iso.org/standard/6084.html

[19] CGA TB-25: Design Considerations for Tube Trailers, 2008

[20] Lloyd's Register ShipRight procedures, Design and Construction, Additional Design Procedures, Risk Based Design (RBD), www.cdinfo.lr.org/information/documents/ShipRight/Design%20and%20Construction/Additional%20Design%20Procedures/Assessment%20of%20Risk%20Based%20Designs%20(ARBD)/Risk_Based_Design_(RBD)_January_2018.pdf

[21] IMO MSC.1/Circ.1212, Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III, 15/12/06

[22] IMO MSC.1/Circ.1455, Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments, 24/06/13

[23] BS EN 1964-1:2000, Transportable gas cylinders. Specification for the design and construction of refillable transportable seamless steel gas cylinders of water capacities from 0,5 litre up to and including 150 litres. Cylinders made of seamless steel with an Rm value of less than 1100 MPa, https://shop.bsigroup.com/ProductDetail/?pid=000000000030026204

[24] ISO 11439:2000 - Gas cylinders - High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles, www.iso.org/standard/33298.html

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