OTC 21309-PP

FPSO SIDE SHELL IMPACT PROTECTION

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Abstract

Traditionally the impact requirements set out by MARPOL for FPSO's and FSO's have been addressed by creating internal cofferdams or external sponsons. Intelligent Engineering has demonstrated that its Sandwich Plate System (SPS), a unique steel-polymer-steel composite materials technology, in the form of a compact double hull (CDH) can offer equivalent protection to either an internal cofferdam or external sponson.

The paper describes the structural engineering study conducted to confirm the impact resistance of the SPS Overlay 20-30-Existing CDH for the prescribed impact between an offshore supply vessel and the FPSO in way of the boat landing area.

Based on the results from the structural dynamic analysis using LS-DYNA, to simulate bow and stern collisions for various collision angle and locations, the following conclusions were made;

- The SPS 20-30-Existing CDH provides an impact resistant hull structure that is able to withstand the minimum accepted industry standard specified design condition 5000 tonne displacement OSV colliding with the specified FPSO at 2m/s without rupture of the crude oil tanks. As an integral part of the FPSO structure, it not only meets but exceeds the requirements of MEPC/Circ 406 "Guidelines for Application of MARPOL Annex I Requirements to FPSOs and FSUs", providing 97,000 kJ of energy absorption capacity
- SPS CDH provides a package of risk reduction benefits over that of cofferdams and external sponsons that include; a significant increase in local impact resistance, a strengthened side shell that reduces critical fatigue stresses, schedule reduction for fabrication and installation, reduced risks during fabrication, less maintenance and eliminates the risks and costs for through life void space inspections.

Further, case studies describe the conversion cost, schedule benefits and operational benefits of the SPS CDH as installed on projects completed to date including the FPSOs P57, P58, MV22 and Aseng. Project approvals have been granted by Det Norske Veritas and the American Bureau of Shipping.

Introduction

Intelligent Engineering Limited (IE) has developed and patented the Sandwich Plate System (SPS), which integrates a steel-elastomer-steel composite structural laminate in place of conventional stiffened steel plates. The resulting structure has greatly enhanced impact absorption capability compared to conventional steel structures.

A study was commissioned by Single Buoy Moorings (SBM) to confirm the feasibility of installing an SPS-based fendering system to protect the side shell structure on an FPSO in way of the boat landing areas. The objective was to design a SPS Overlay solution to meet the relevant requirements of IMO MARPOL Annex I and eliminate the need to install cofferdams in these areas, thus maximising the deadweight capacity of the FPSO, minimizing conversion and life cycle costs of the asset, reducing inspection and maintenance requirements and creating an inherently safer design both in terms of construction and operation.

This paper describes objectives of the study, requirements for the confirmatory analysis, the design conditions, analysis methodology and gives a summary of results that confirm the improved impact resistance of two SPS Overlay solutions, with either a 20 mm or a 30 mm steel overlay faceplate and a 30 mm polyurethane elastomer core, fendering systems to impact between an offshore support vessel and a typical FPSO.

Objectives

The objective of the study was to confirm the ability of SPS structure applied to the boat impact area of the FPSO to satisfy the requirements of IMO MEPC/Circ 406 "Guidelines for Application of MARPOL Annex I Requirements to FPSOs and FSUs."

The interpretation of the IMO requirements (design conditions) and acceptance criteria of the confirmatory analyses were defined independently by the American Bureau of Shipping (ABS), Lloyd's Register (LR) and Det Norske Veritas (DnV). The use of SPS Overlay in this type of low energy collision resistance application has been approved in principle by each of these class societies as long as these requirements and acceptance criteria are met using industry standard and confirmatory analyses. Further projects to install SPS CDH on four FPSO's have been approved and implemented, three Classed with ABS and one with DnV.

Scope of the Engineering Study

The following identifies the scope of the work:

- Acquire the technical details drawings, specifications, mass and other data for the FPSO and OSV to permit accurate modelling of vessel.
- Benchmark numerical validations of impact tests to verify the numerical simulation of SPS plates and to establish material models and bond failure models. Develop a description of analysis methodology and assumptions.
- Create finite element models in LS-DYNA simulating the structural arrangements of the OSV and the FPSO. Note that the idealisation of the FE models should ensure that the calculated critical deformation energy at rupture for each collision case is realistic. In the areas of the striking position a refined mesh, consistent with standard (recommended) practice will be used. This mesh density will also be used at the connection of the impacted side shell longitudinal stiffeners to the adjacent web frames, including the stiffener bracket. SPS structure, steel plates, web plates and transverse web frames will be idealised using a combination of solid-shell elements and solid elements.
- Report on result sets for 8 collision load cases for bow and stern collisions occurring either at a web frame or between web frames perpendicular or oblique to the FPSO side shell with SPS Overlay fendering. Results are to be given in sufficient detail to provide data on deformations (contour plots), stresses, absorbed energies, and rupture (if any) of cargo containment boundary. Prepare deformation energy curves versus penetration depth.
- Development of all details and drawings of the SPS structure.
- Review of IMO MEPC requirements and confirmation from the Classification Societies that proposed analysis will meet their requirements for assessment
- Confirm the commercial and economic viability of the proposed SPS Overlay solution.

Additional analyses were conducted for the critical bow and stern impacts at higher impact velocities to determine collision energy required to induce hull rupture and to understand the behaviour of the existing steel FPSO and the FPSO with SPS Overlay during these events. Additional of analyses were conducted to determine the influence of varying failure criteria on the energy absorption capacity at hull rupture.

Further analyses were conducted to compare the energy absorption capacity of the SPS Overlay solution to the use of current solutions using either a sponson (in this particular case) or an internal cofferdam. One possible solution is to provide a double hull type construction with the spacing between the sponson shell and the FPSO hull being in the range between 2000 mm or 3000 mm to provide the necessary impact and rupture resistance. For this analysis, it was assumed that the sponsons would be constructed with plate and stiffener scantlings similar to the existing FPSO hull. The rupture resistance was evaluated for the same conditions as the most severe collision event as determined for the original structure.

Acceptance Criteria

In accordance with MEPC/Circ 406 "Guidelines for Application of MARPOL Annex I Requirements to FPSOs and FSUs", the FPSO side structure must be capable of absorbing the energy created as a result of a collision by an offshore support vessel (OSV) with the side shell structure without rupture of the crude oil tanks, (i.e. no crude oil outflow).

The collision analyses must therefore confirm that the SPS Overlay side shell structure can withstand the impact without penetration or rupture under the specified design condition.

Specified Design Condition

The kinetic energy to be absorbed shall be calculated using:

$$E = \tfrac{1}{2}(m+a)\,v^2$$

where,

- m = displacement of the support vessel collision
- a = 10% for bow and stern collision added mass of the support vessel, normally assumed to be 40% for sideways
- v = impact speed of the support vessel

According to ABS, LR, and DnV, the minimum accepted industry standard for the specified design condition is an impact of a support vessel with 5000 tonnes displacement at an impact speed of 2 m/s. The class societies state that the designer and/or owner can base their calculations on the displacement of a specific vessel that is designated to serve that particular FPSO when the displacement is less than 5000 tonnes, but then their approval will be restricted to the use of that designated support vessel. ABS, LR and DnV recommend that industry accepted dynamic analysis with appropriate finite element software be used to simulate bow and stern collisions for various collision angle and locations.

Analysis Method, Modelling Assumptions and SPS Overlay Design

In accordance with the Class recommendations, Intelligent Engineering selected LS-DYNA software, considered as an "Industry Standard" for crashworthiness or collision simulations for the analyses. SBM specified the candidate FPSO and the 5000 tonne displacement OSV for the collision simulations.

Intelligent Engineering developed a specification for the analytical work (material modelling and verification, benchmark problems for local impact, and the collision scenarios). Intelligent Engineering assembled the relevant data and created the solid models for analysis. Since IE does not have a LS-DYNA licence, it subcontracted the finite element model creation, analysis and collation of the results to ROI Engineering Inc., a Toronto based engineering company with the appropriate licences, technical capability and experience. Intelligent Engineering designed the SPS Overlay fendering solution, verified all modeling and analyses, and prepared the final report.

<u>FPSO and OSV Models</u>

The analyses consider the collision between 2 objects, the struck vessel, in this case the FPSO and an example 5000 tonne displacement offshore support vessel. For this study, an anchor-handling tug supply vessel (AHTS, from this point referred to simply as OSV) with a cargo mass reduced to give a displacement of 5000 tonnes was used as the colliding ship. This change reduces the design draught of the OSV from 7.5 m to 5.2 m. Similarly, the draught for the FPSO was reduced from 21.0 m to 11.9 m so that the top of the OSV bow impacts below the gunwale plating. The particulars, including operating draughts, for the OSV and the FPSO are given in Table 1 and the geometries of the colliding portions of the ships are shown in Figure 1. Figure 1d shows the relative position of the colliding ships.

Table 1 – Comparison of OSV and FPSO Vessels

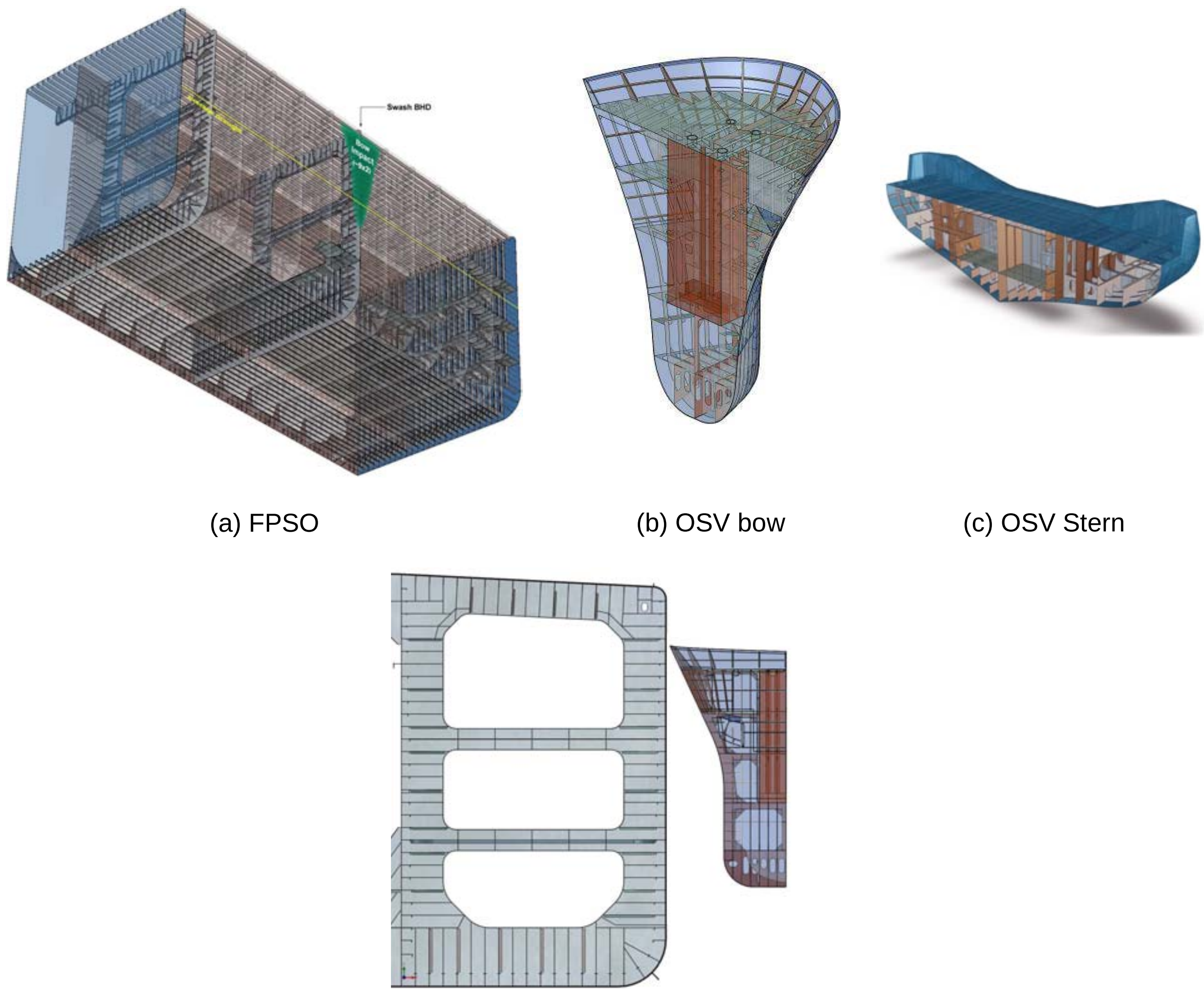
	Units	OSV	FPSO
Length between perpendiculars, LBP	m	72.0	320.0
Breadth moulded, B	m	18.8	54.5
Design draught moulded, D	m	*5.15*	*11.864*
Block Coefficient, C_b	-	*0.70*	0.8302
Density of seawater, $\rho_{seawater}$	kg/m^3	1025	1025
Displacement (mass loaded ship to bring it to draught) M = LBP x B x D x C_b x $\rho_{seawater}$	tonnes	*5002*	*176,070*
Dead Weight (cargo mass to bring to draught)	tonnes	*1075*	133,307
Mass of ship with no cargo	tonnes	3,927	42,763
Length (Overall)	m	82.0	337.058
Depth Moulded	m	9.0	27.0
Centre of Buoyancy from Midships	m	-	-3.256

The structural arrangements of both vessels were modeled in sufficient detail to allow the behaviour of structure local to the impact area to be simulated. Elaborate details such as limber holes, cut-outs and tapered flanges were either omitted or simplified. A parametric study was conducted to determine whether the extent of the original model could be reduced to truncate runtimes. Analyses of the original model and a reduced model, which are shown in Figure 2, gave identical results (same internal energies, deflections, and strains). Adequate reduced models were used for all subsequent analyses.

Initial analyses permitted the structural deformation of both vessels. For the OSV bow collisions it was found that 70-80% of the impact energy was absorbed by the bow. The OSV stern is significantly stiffer than the bow and absorbs only 5% of the impact energy. Since the proportion of absorbed energy is relatively small, the rigid body stern model was used for all subsequent analyses for stern impacts. This simplification reduced computational times and gave slightly more conservative results as the FPSO must absorb approximately 5% more energy.

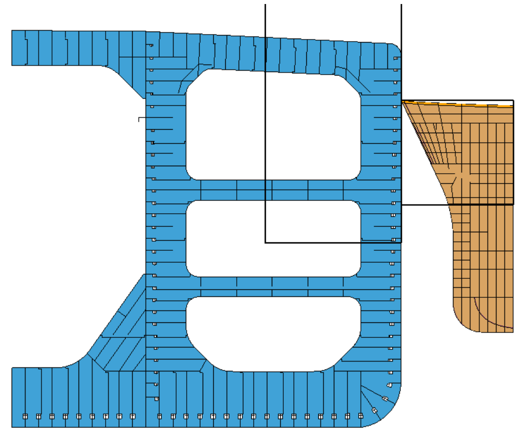
As recommended by Class, allowance for added mass and a plate corrosion allowance of 1.5 mm for all FPSO elements has been made. The struck vessel was assumed to be floating freely with no velocity. Conservatively, no rigid body motion of the “coupled” vessels was allowed after impact. The boundary conditions for the reduced model are shown in Figure 3.

A total of 8 collision cases, as shown in Table 2, were examined for bow and stern collisions occurring either at a web frame or between web frames perpendicular or oblique to the FPSO side shell.

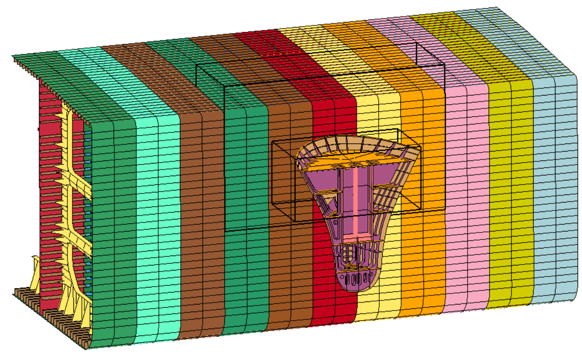


(a) FPSO (b) OSV bow (c) OSV Stern

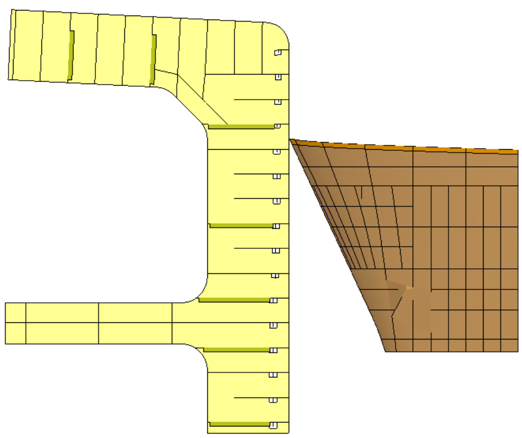
Figure 1 – FPSO 3D-CAD Model of Colliding Sections of the FPSO and OSV



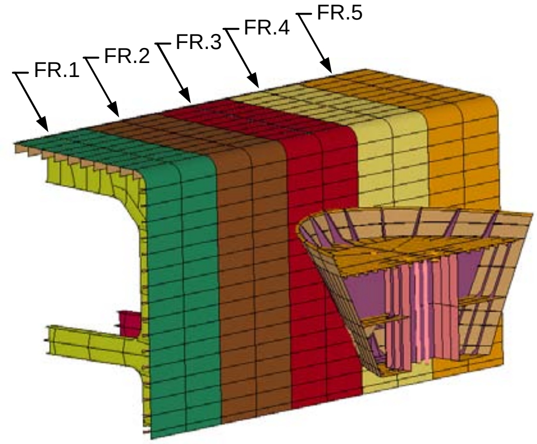
(a) extent of original model – section



(b) extent of original model – oblique view

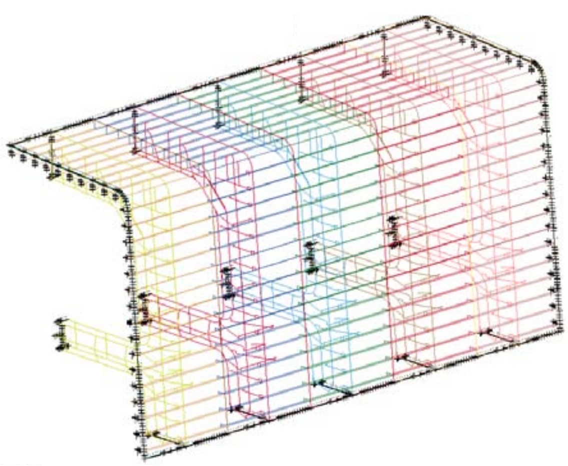


(c) extent of reduced model – section



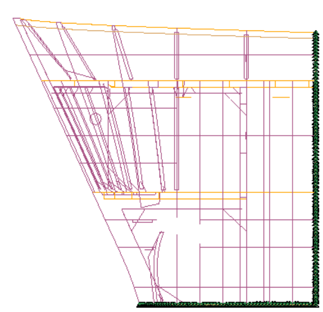
(d) extent of reduced model – oblique view

Figure 2 – Comparative Analysis of Reduced Model



(a) FPSO boundary conditions

- fixed DOF on all FPSO free edges

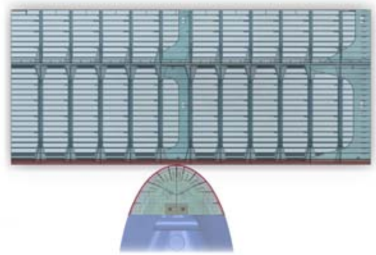
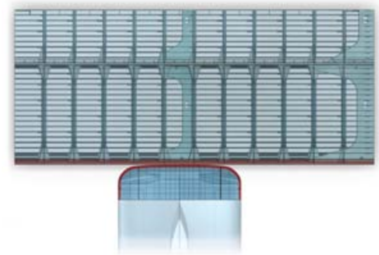
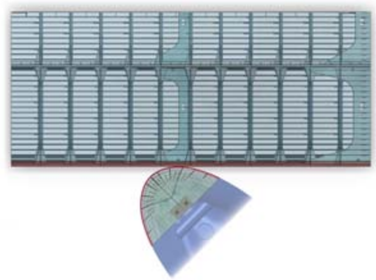
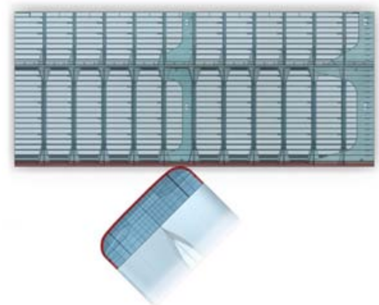
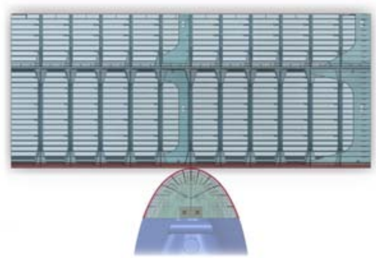
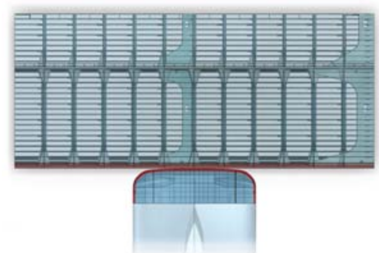
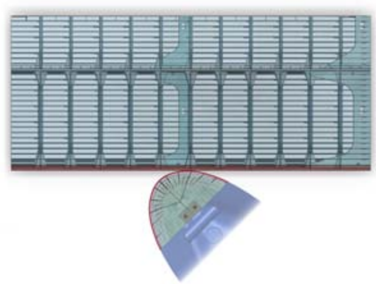
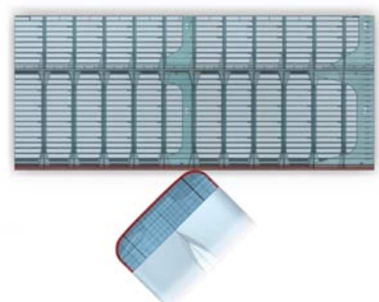


(b) OSV bow boundary conditions

- nodal rigid body (added mass) on OSV;
- only direction of travel is free on rigid body;
- CG of rigid body motion on plane at draught level;
- initial velocity applied to all OSV bow nodes

Figure 3 – Reduced Model Boundary Conditions

Table 2 – Eight Collision Scenarios for the Numerical Simulation Study

Location	Bow impact	Stern impact
Colliding vessel at 90° between two web-frames		
Colliding vessel at 45° between two web frames		
Colliding vessel at 90°at a web frame location		
Colliding vessel at 45°at a web frame location		

Failure Criteria

Several element failure criteria may be set in LS-DYNA. Typically, an equivalent plastic failure strain is defined and when the element reaches this failure strain, the element is deleted from the model. A study conduced by Lehmann et al (2001) for Germanischer Lloyd, identified that the element types and mesh density (element sizes) changes the failure behaviour. When using a fine mesh with solid elements, where the length of the necking zone is similar to the plate thickness, the necking process can be adequately simulated. For ship collision models, the element sizes are generally larger and as a result the failure strain criteria must be modified to suit. To determine which failure strains should be used for their ship collision calculations, failure strains determined by thickness measurements of damaged structural details of real collision cases and of full-scale collision test models were used, Lehmann et al

(2001). Based on this work, the failure strain for different element sizes were calculated using Equation 1.

$$\varepsilon_f = 0.056 + \frac{0.54t}{l_e} \tag{1}$$

where,

ε_f = failure strain
t = plate thickness
l_e = element length

For the FPSO hull plating, rupture of the hull plating occurs when the equivalent plastic failure strain reaches 17% because the element length is ~100 mm and the plate thickness is 21.5 mm. When the failure strain limit is reached in an element it is deleted and the analysis continues. The same failure criterion was applied to the SPS Overlay faceplate.

The equivalent plastic failure strain does not differentiate between tensile and compressive strain, hence for the web frames which buckle under compression during the collision events, the failure strain limit was not set (no deletion of elements). The strain limit was not set for the longitudinal stiffeners as these tended to buckle at the web frames early in the collision event which led to a deletion of elements and a less stiff hull plate that was not considered to be realistic. Longitudinal stiffeners on the hull plate may reach the equivalent plastic failure strain, primarily in tension, at or about the same time as the hull plating, hence setting the limit for the plating will correctly identify rupture and having no limit for the stiffeners will not affect the result.

The failure strain limit was not set for the OSV as rupture of this vessel is either not likely (small plastic deformation of the stern) or is of no consequence to the energy absorption behaviour of the FPSO during the collision (rupture of the striking vessel does not affect the rupture of the struck vessel).

SPS Overlay Design

The selection of the SPS Overlay faceplate thickness and elastomer core thickness is a function of the local and global energy absorption design requirements; the fabrication and geometric constraints.

The amount of energy absorption in ship collisions is directly proportional to the volume of plastically deformed steel, Minorsky (1959). In the case of an SPS Overlay where more steel volume is added to the existing structure, the design involves selecting an Overlay plate scantling that would produce the desired increase in energy absorption. The existing FPSO hull plate thickness is 23 mm, which was reduced in accordance with the applicable plate corrosion allowance to 21.5 mm. To give a balanced hull plate section with a plate thickness that satisfies the desired increase in energy absorption, an SPS Overlay plate thickness of 20 mm was selected. This plate is also sufficiently thick to resists local punctures while remaining constructible and economic (standard weld sizes, consistent with common shipbuilding practice).

Typical SPS Overlays involve cleaning the existing plate, welding solid steel perimeter bars to form the boundary elements to which the SPS Overlay faceplate is welded and injecting elastomer into the cavity.

For both low energy and high energy impacts it is recommended to substitute these solid bars with a collapsible rectangular hollow structural section, RHS 50x30x5. The RHS perimeter bars are to be positioned over web frames and side shell longitudinals as shown in Figure 4. In a collision event, these RHS sections will collapse thereby reducing the effect of the hard spot and probability of local rupture. In addition the shape and thin wall provide a section that is more resistant to crack propagation (indirect path) should a crack form in either the existing hull plate or the SPS Overlay faceplate. This effectively provides an independent secondary steel barrier against oil outflow should one of the plates rupture before the other.

The minimum RHS depth establishes the minimum depth of the core to be 30 mm. In low energy impacts (1000 kJ or less), this core thickness is sufficient to absorb a substantial amount of energy through its thickness in compression and to dissipate localized bending strains, thereby preventing localized rupture.

For higher energy global impacts (10,000 kJ or greater), the core absorbs only about 1% of the total impact energy. Making the core thicker would not improve the energy absorption capacity by any sizable amount hence a 30 mm core thickness is deemed sufficient.

The layout of SPS Overlay faceplates and typical weld details for the side shell structure are given in Figure 4. The SPS 20-30-existing Overlay is applied to the side shell from the start of the gunwale radius to the start of the bilge radius on either side of the cargo hold where vessels are moored during oil offloading, where increased probability impact would exist. The plates are oriented longitudinally over the length of the cargo hold for the following reasons:

- to be consistent with standard shipbuilding practice,
- to be more conducive to SPS Overlay where vertical injections are made without restraint in multiple injection lifts, and
- to decrease the probability of impact on the RHS perimeter bar or the intersection of these bars.

<u>SPS Overlay Modeling</u>
The SPS Overlay consists of 20 mm thick Overlay plate and a 30 mm thick core and is applied to the side shell from the top of the bilge radius to the start of the gunwale radius. The SPS Overlay is modeled with shell elements for the Overlay plate, the elastomer core is modelled with two solid elements through the thickness and the existing plate is modeled with shell elements. For this combination of elements, modeling the bond using the CONTACT_TIEBREAK elements between the steel faceplates and the elastomer core was not possible. Therefore, the SPS layers are fully bonded together and the normal stress and shear stress results will be compared to the failure curve given in Kennedy and Ferro (2007) to determine whether bond failure has occurred.

Comparison of the Energy Absorption Characteristics, SPS Overlay vs the Original Construction
The SPS 20-30-existing Overlay applied to the struck FPSO must be capable of absorbing the energy created as a result of a collision with the OSV without resulting in rupture of the crude oil tanks. Because rupture of the existing hull plating must be prevented, the worst design case would be when the collision event produces the greatest equivalent plastic strain on the existing hull. If this exceeds the failure limit, then rupture has occurred. From collision simulations between the steel FPSO and the OSV, it was found that the worst design cases (highest strain on hull plate) were the stern oblique impact on a web frame and the bow orthogonal impact on a web frame. The results from these collision simulations are presented herein for both the original structure and for the same structure with the SPS Overlay.

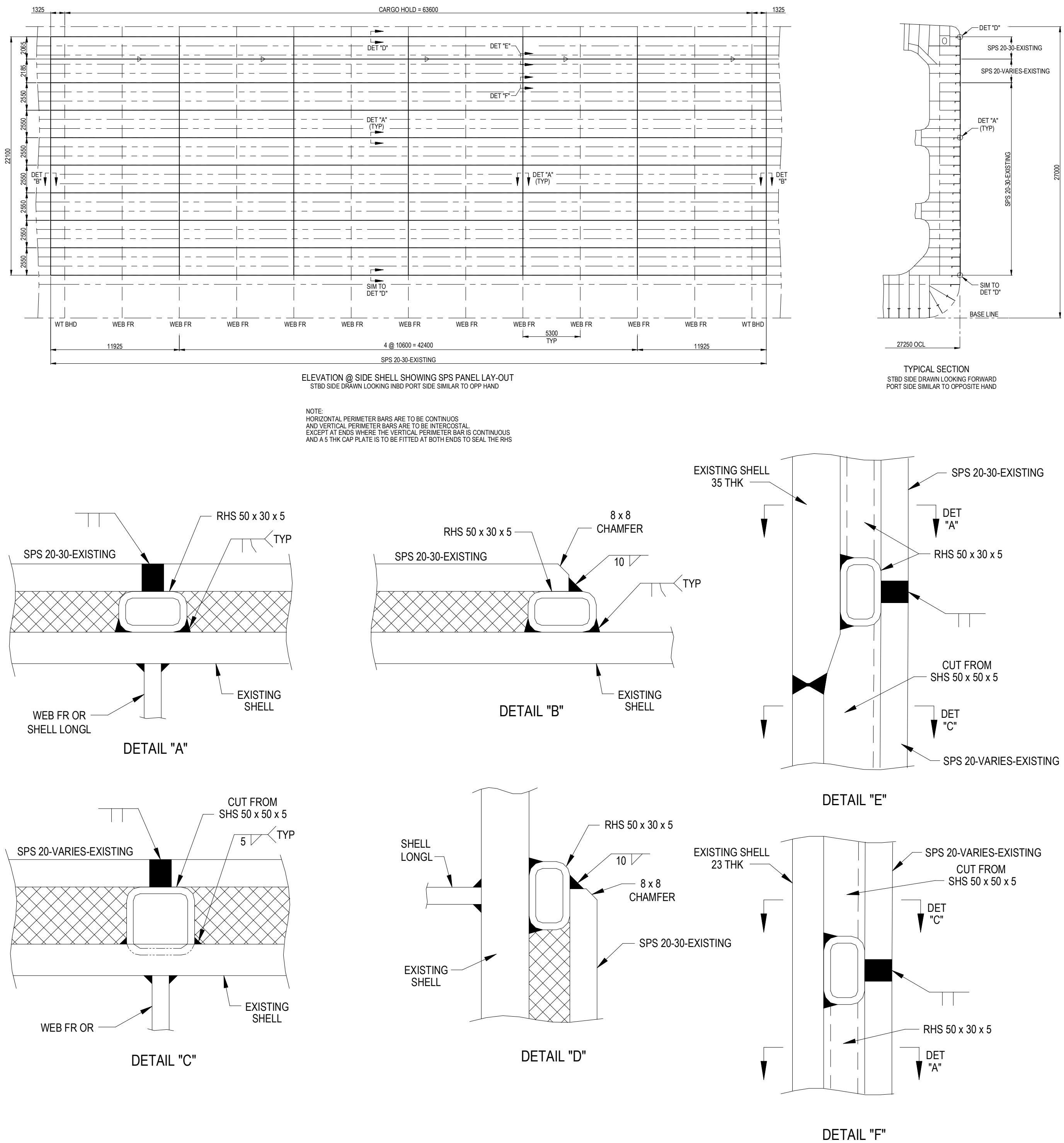


Figure 4 – SPS Overlay for FPSO Fendering Drawing

<u>Stern Oblique Impact on a Web Frame</u>

Contour plots showing the equivalent plastic strain and deflections at the point when the kinetic energy has been fully absorbed are shown in Figure 5 and Figure 6, respectively. The peak strains of 9% shown in Figure 5 for the hull plate are only 54% of the equivalent failure strain 17%, therefore no rupture of the hull would occur. With the SPS Overlay, the existing hull plate has the same strain value, but it occurs over a smaller area. The SPS Overlay plate has strain values of only 4%, which means this plate has more capacity and for larger impact velocities it should absorb significantly more kinetic energy before rupture. Based on the analyses completed to date, it is anticipated that the existing hull plate will rupture prior to the SPS Overlay faceplate. The latter will provide a secondary steel barrier thereby preventing oil outflow and it will also continue to provide additional energy absorption capacity.

As shown in Figure 6, the maximum deflection of the hull for the steel FPSO and the FPSO with SPS Overlay is 677 mm and 579 mm, respectively. The time to reach these displacements represents the time when the kinetic energy of the impact has been fully absorbed. For the steel FPSO and the FPSO with SPS Overlay, the time to fully absorb the kinetic energy occurs at 750 ms and 668 ms, respectively. The SPS Overlay is stiffer than the steel structure as it is capable of stopping the colliding vessel in less time and with less deformation.

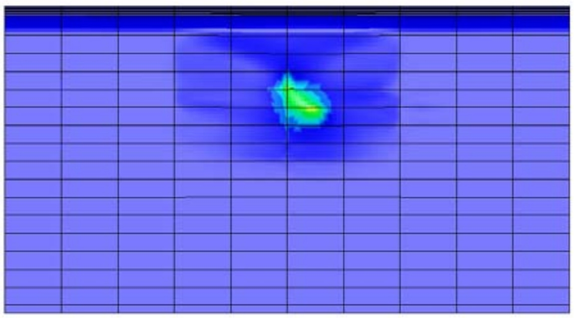
The internal energy versus time data plotted in Figure 7 is summarized in Table 3 and provides a comparison of the distribution of internal energies for the existing structure and the same with SPS Overlay. Note, for the existing structure (all-steel) the energy absorbed by the hull plate is increasing relative of the web frames or stiffeners. For higher energy impacts most of the additional energy is most likely to be absorbed by the hull plating as the framing members are buckled and have little or no additional energy absorption capacity.

With the SPS Overlay the hull internal energy drops 39% from 4.7 MJ to 2.9 MJ as the internal energy is redistributed to the SPS Overlay plate. Not only does the redistribution of internal energy reduce the contribution of the existing hull, but also for this load condition, it also reduces the energy absorbed by the web frames and the longitudinal stiffeners. The existing structure absorbs less energy (has more residual energy absorption capacity) and for similar structural conditions or for similar collision events less potential for rupture, excluding the added capacity not yet fully utilized of the SPS Overlay faceplate.

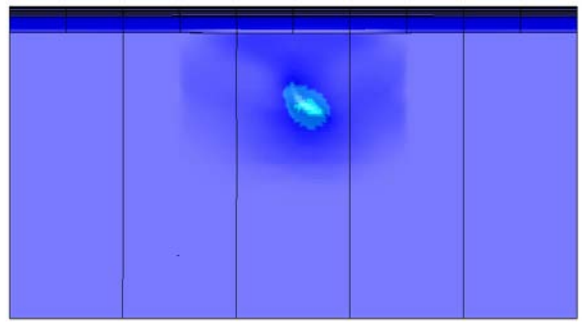
Additional analyses were conducted with increased velocity for the critical load case to determine the kinetic energy required to cause rupture for the existing structure and the same with an SPS Overlay. It was determined that the ratio of the two kinetic energy values quantify the added energy absorption capability of the SPS Overlay system for the same set of conditions. Should the conditions vary for the existing structure, thinner hull plating, longitudinal stiffeners or web frame due to corrosion for example, then the ratio of energy absorption capacity and absolute magnitude will be informative as to determining the relative energy capacity under these modified conditions.

Table 3 – Redistribution of Internal Energies with SPS Overlay for Oblique Stern Impact on Frame

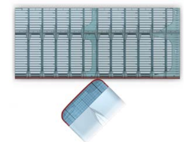
	Time to Peak Deflections	Hull	SPS Overlay Plate	Elastomer	Web Frame	Stiffeners	Total Internal Energy
	ms	MJ	MJ	MJ	MJ	MJ	MJ
Steel	749.5	4.69	NA	NA	3.87	2.26	10.82
SPS Overlay	667.5	2.85	2.32	0.15	3.63	1.94	10.89
% difference	-10.9	-39.2	-	-	-6.2	-14.2	-

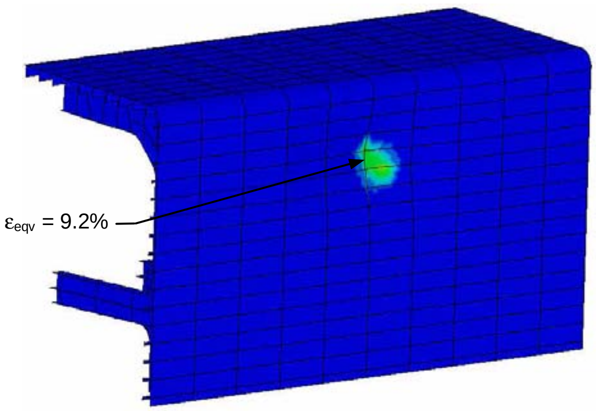


(a) steel – elevation at t = 0.75 sec

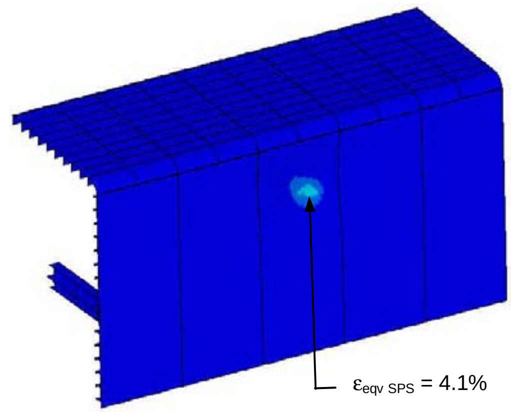


(b) SPS Overlay – elevation at t = 0.67 sec

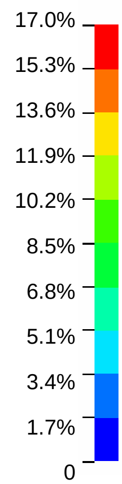


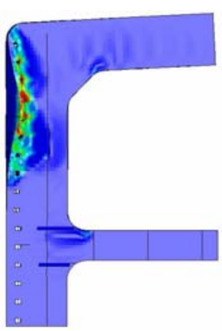


(c) steel – oblique view from outside at t = 0.75 sec

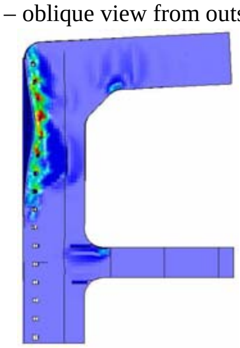


(d) SPS Overlay – oblique view from outside at t = 0.67 sec

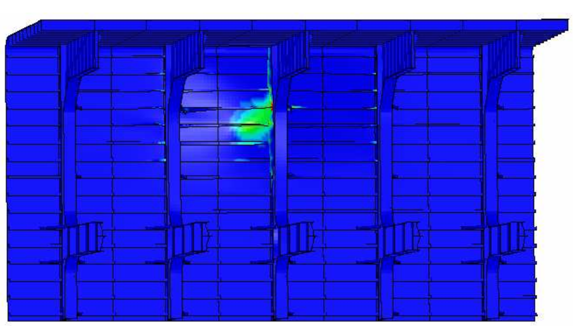




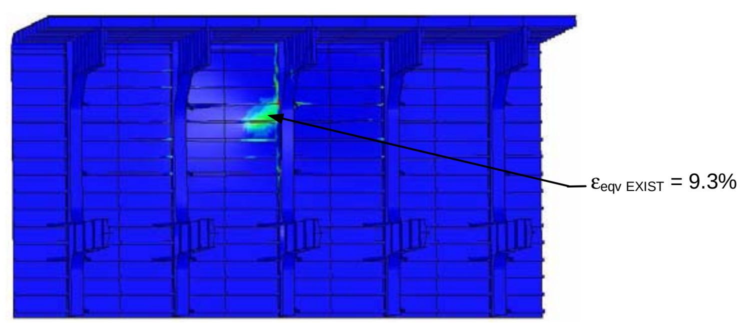
(e) steel – section at t = 0.75 sec



(f) SPS Overlay – section at t = 0.67 sec

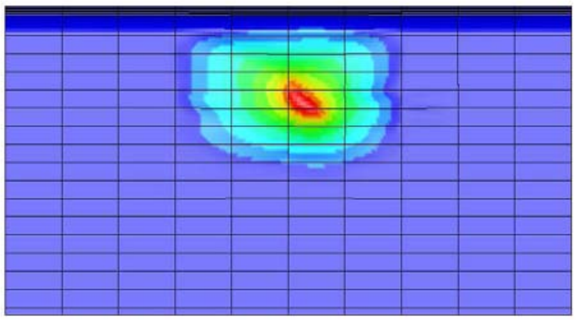


(g) steel – oblique view from inside at t = 0.75 sec

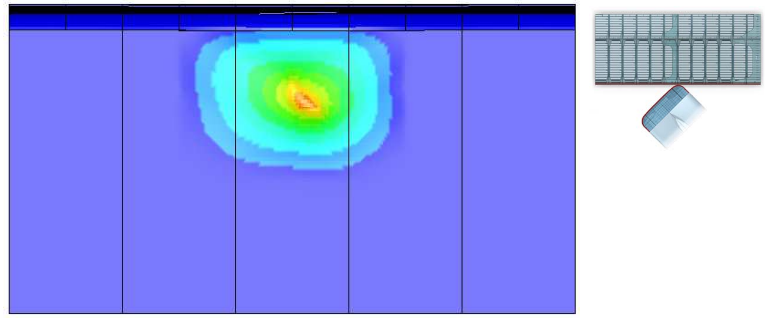


(h) SPS Overlay – oblique view from inside at t = 0.67 sec

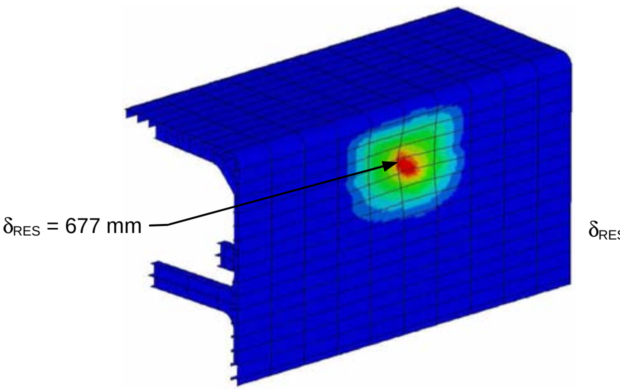
Figure 5 – Equivalent Plastic Strain Results from Stern Oblique Impact on Frame



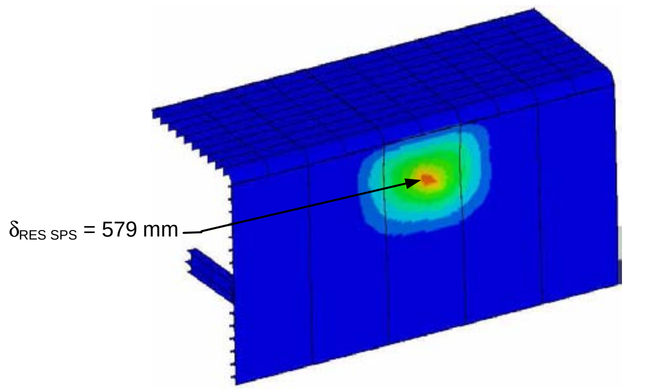
(a) steel – elevation at t = 0.75 sec



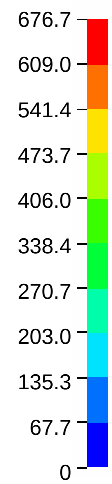
(b) SPS Overlay – elevation at t = 0.67 sec

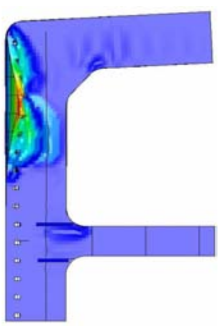


(c) steel – oblique view from outside at t = 0.75 sec

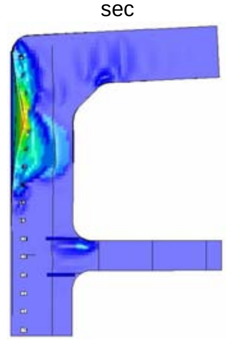


(d) SPS Overlay – oblique view from outside at t = 0.67 sec

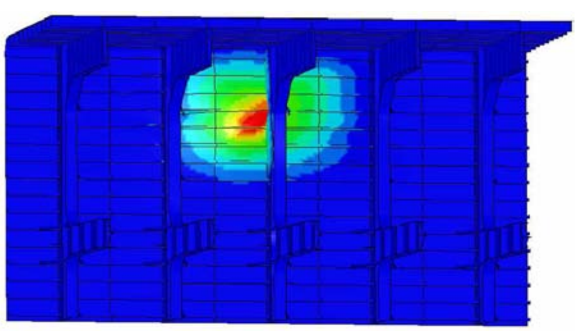




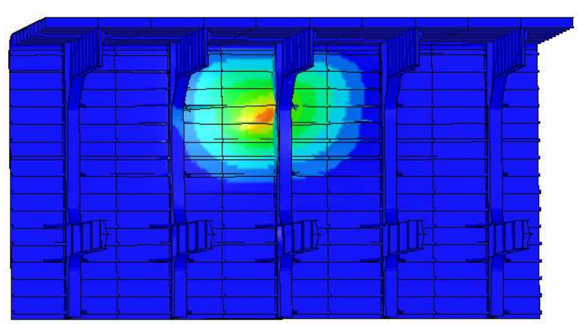
(e) steel – section at t = 0.75 sec



(f) SPS Overlay – section at t = 0.67 sec

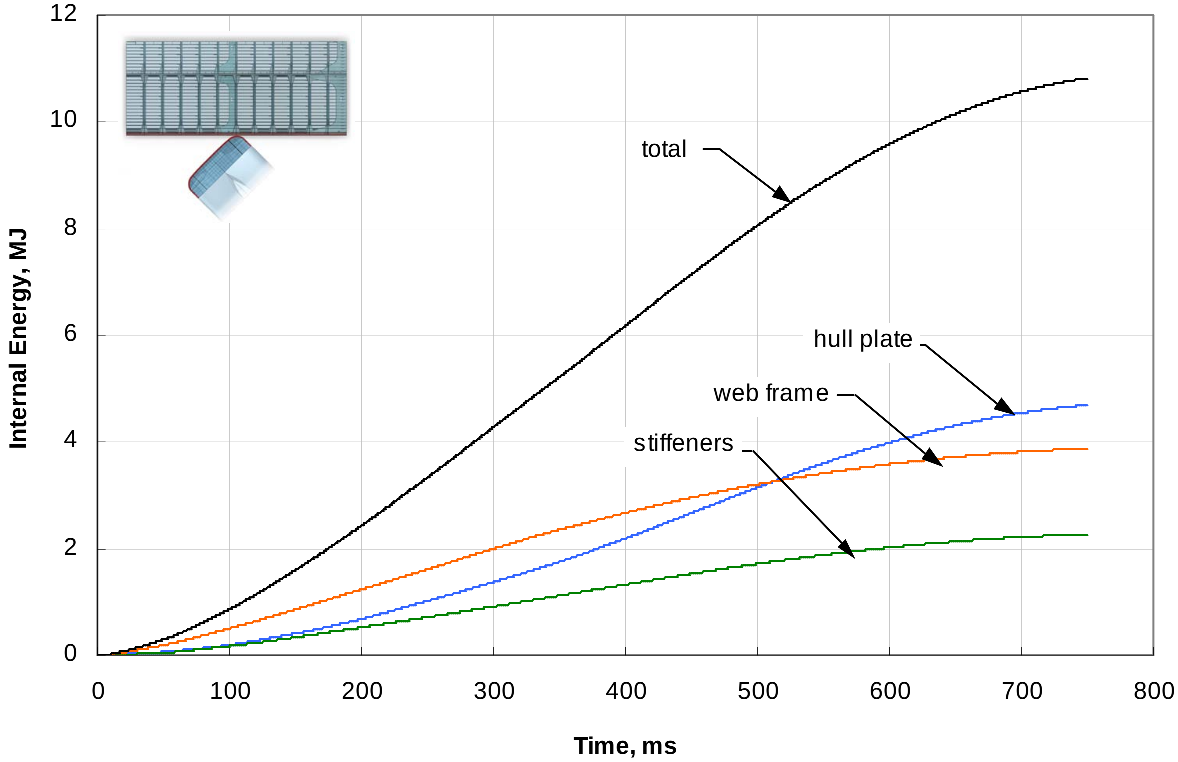


(g) steel – oblique view from inside at t = 0.75 sec

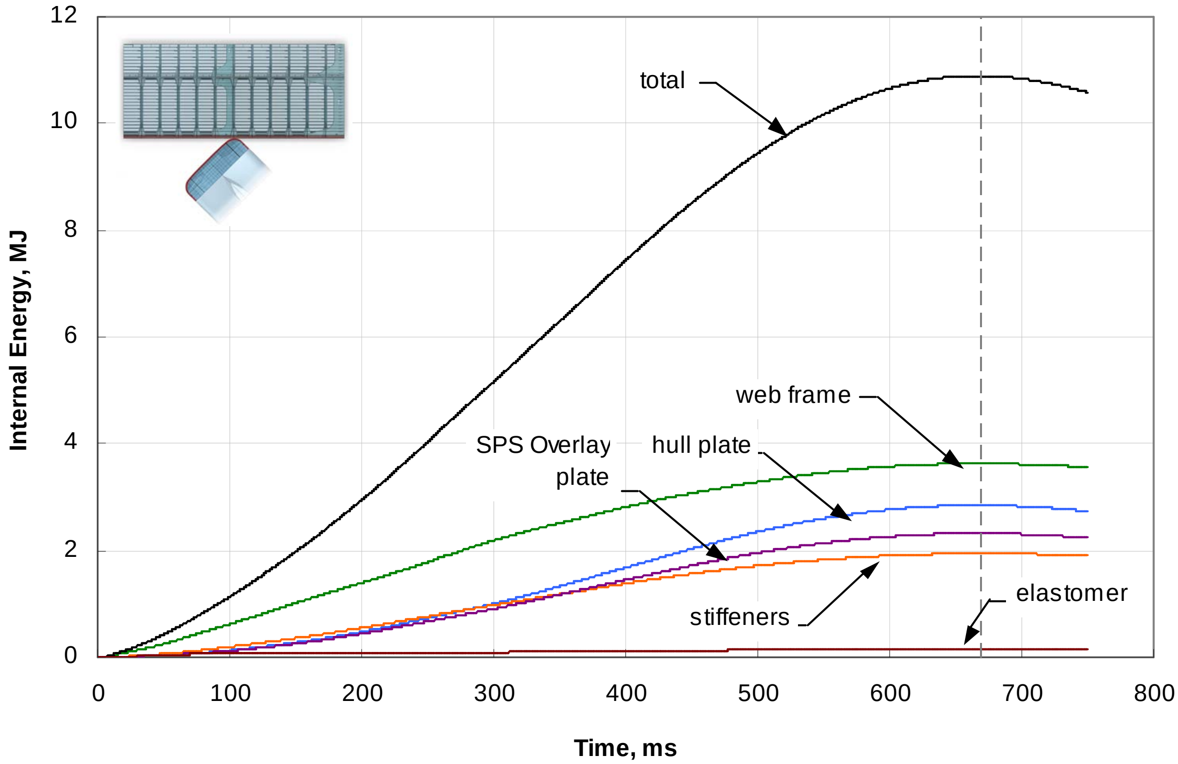


(h) SPS Overlay – oblique view from inside at t = 0.67 sec

Figure 6 – Resultant Deflection Results from Stern Oblique Impact on Frame



(a) steel



(b) SPS Overlay 20-30-Existing

Figure 7 – Internal Energy vs. Time for Stern Oblique Impact on Frame

Stern Oblique Impact on a Web Frame

Unlike stern collisions, approximately 70-80% of the bow impact energy is absorbed by the bow of the OSV when colliding with the FPSO. On contact with the FPSO, the bow bulwark (portion of bow extending above the strength deck) bends back towards the strength deck as shown in Figure 8. After this occurs, the OSV strength deck comes into contact with the FPSO hull at which point the FPSO hull begins to absorb energy and the contact force between the two vessels increases rapidly.

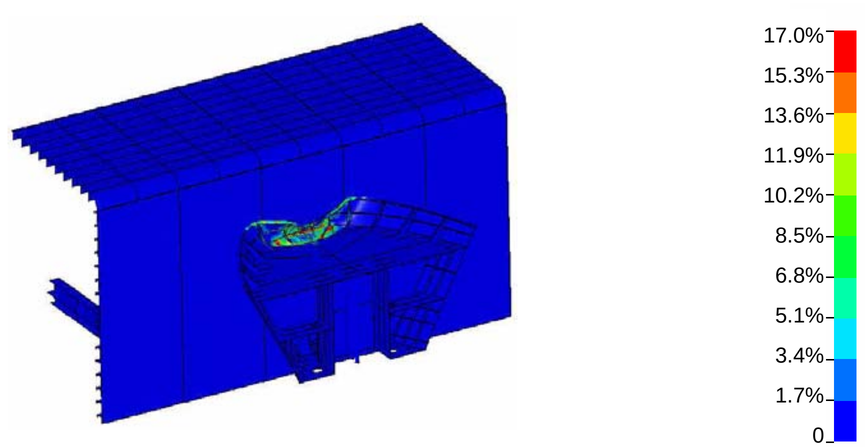


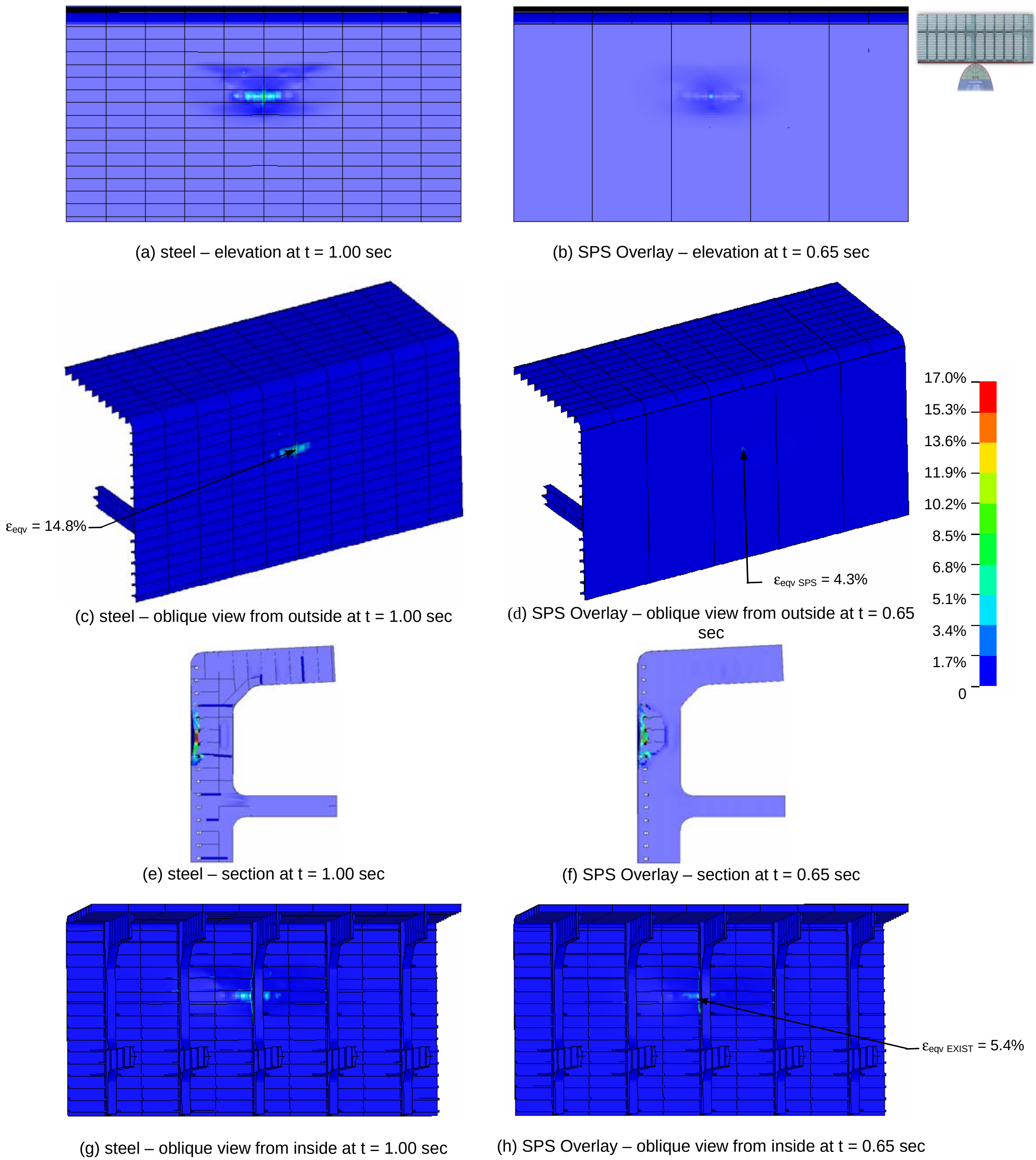
Figure 8 – Bow Collision Failure Equivalent Strain Results

Contour plots showing the equivalent plastic strain and deflections at the point when these peak are shown in Figure 9 and Figure 10, respectively. For the steel FPSO and FPSO with SPS Overlay the peak equivalent strains for the hull plate are 14.8% and 5.4%, respectively. These values are less than the defined failure strain of 17%, hence there is no rupture of the hull for this collision event and specified conditions. The SPS Overlay faceplate has strain values of only 4.3%. The SPS Overlay is very effective in protecting the existing hull plate as it reduces the equivalent plastic strain on the existing hull by 64% and since both the SPS Overlay faceplate and the existing hull exhibit lower values of equivalent plastic strains, there is substantially more capacity for the structure to absorb higher kinetic energy impacts (greater velocities) without hull rupture.

As shown in Figure 11, the peak deflection of the hull for the steel FPSO and the FPSO with SPS Overlay are 313 mm and 208 mm, which occur at 1000 ms and 650 ms, respectively. The SPS Overlay structure is stiffer than the existing structure. Since the bow is colliding against a stiffer structure, the collapsible bow absorbs ~12% more energy than the existing structure. This is illustrated in the internal energy vs time data plotted in Figure 11 and summarized in Table 4, which lists the distribution of the internal energy within both FPSO structures and the bow of the striking vessel. SPS Overlay changes the dynamic behaviour of structure, redistributes and reduces the internal energy contribution of the existing hull, web frames and the stiffeners by 69%, 26% and 34%, respectively. Even though the relative energy contributions are lower than the stern impact, the localized equivalent plastic strains in the hull were close to rupture for the existing structure. A small increase in velocity or rfeduction in existing plate thickness could lead to rupture. The structure with SPS Overlay has substantially more energy absorption capacity.

Table 4 – Redistribution of Internal Energies with SPS Overlay for Orthogonal Bow Impact on Frame

	Time to Peak Deflections	Hull	SPS Overlay Plate	Elastomer	Web Frame	Stiffeners	Bow	Total Internal Energy
	Ms	MJ	MJ	MJ	MJ	MJ	MJ	MJ
Steel	1000	1.10	-	-	1.24	0.56	7.92	10.80
SPS Overlay	650	0.34	0.31	0.09	0.92	0.37	8.86	10.83
% difference	-35	-69.1	-	-	-25.8	-33.9	+11.9	-



(a) steel – elevation at t = 1.00 sec

(b) SPS Overlay – elevation at t = 0.65 sec

(c) steel – oblique view from outside at t = 1.00 sec

(d) SPS Overlay – oblique view from outside at t = 0.65 sec

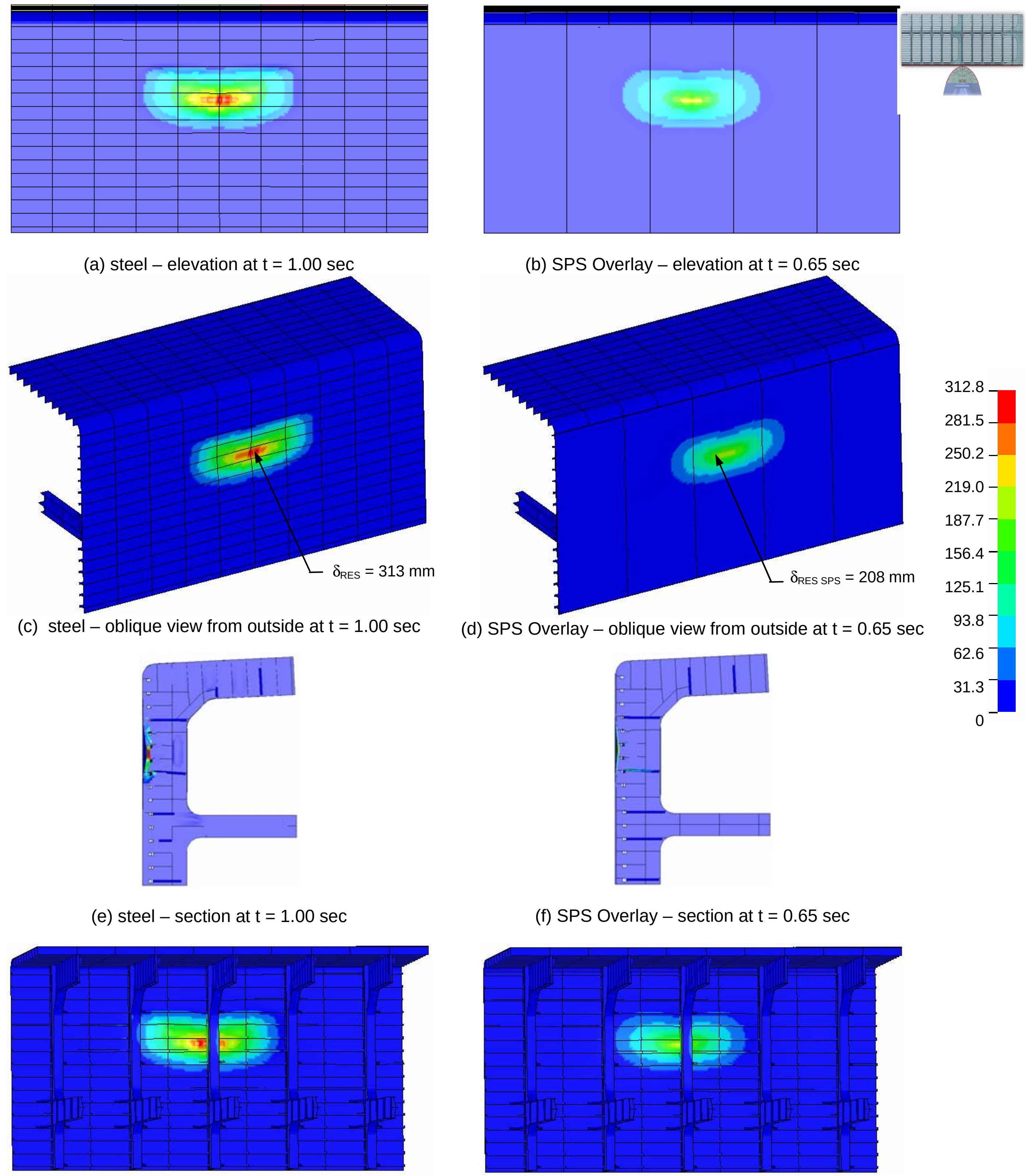
(e) steel – section at t = 1.00 sec

(f) SPS Overlay – section at t = 0.65 sec

(g) steel – oblique view from inside at t = 1.00 sec

(h) SPS Overlay – oblique view from inside at t = 0.65 sec

Figure 9 – Equivalent Plastic Strain Results from Bow Orthogonal Impact on Frame



(a) steel – elevation at t = 1.00 sec

(b) SPS Overlay – elevation at t = 0.65 sec

(c) steel – oblique view from outside at t = 1.00 sec

(d) SPS Overlay – oblique view from outside at t = 0.65 sec

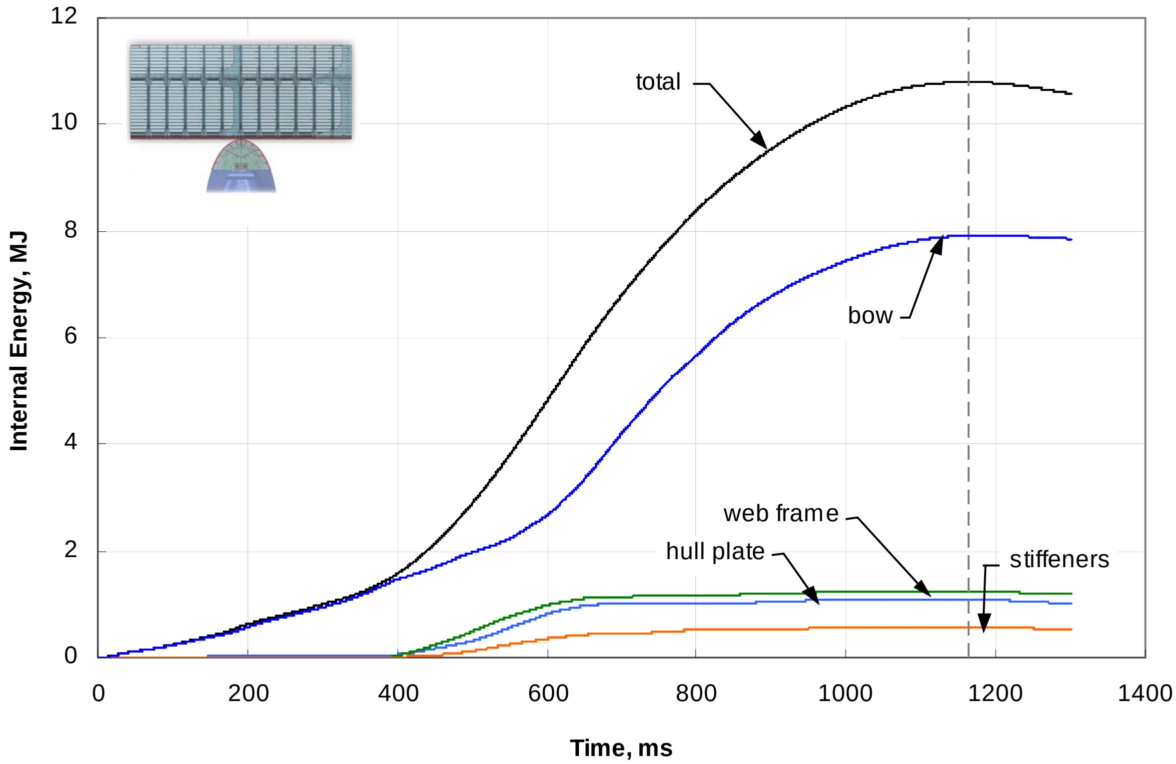
(e) steel – section at t = 1.00 sec

(f) SPS Overlay – section at t = 0.65 sec

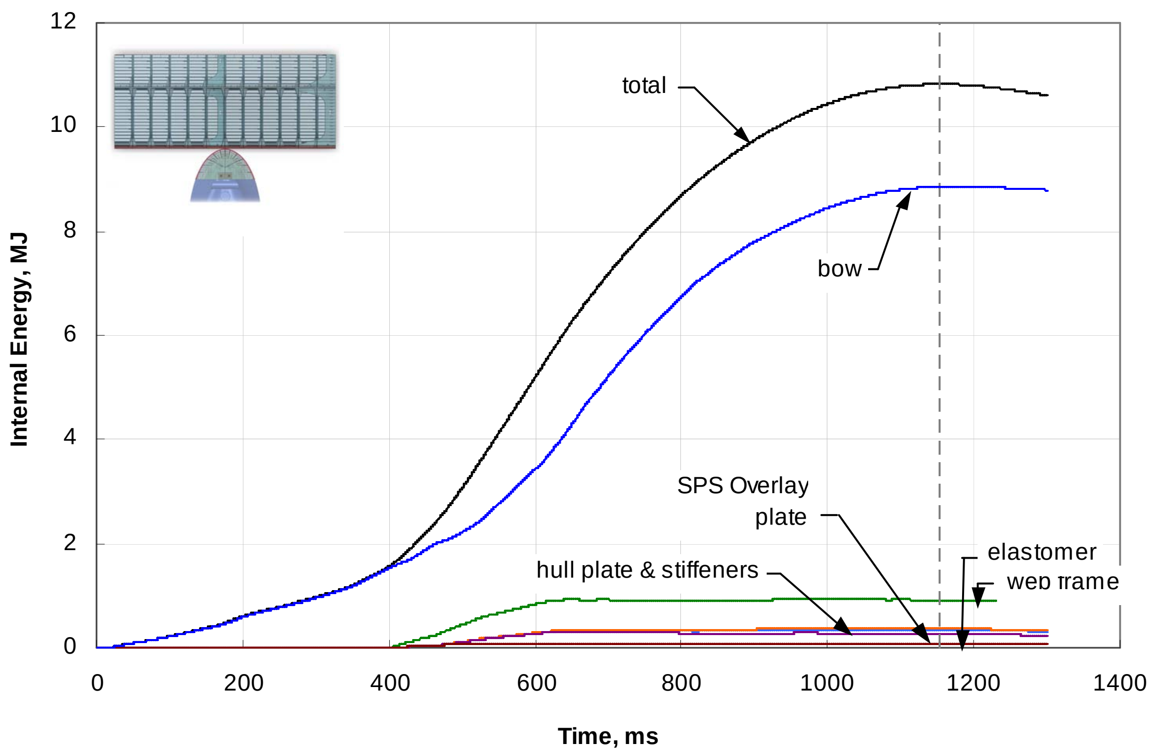
(g) steel – oblique view from inside at t = 1.00 sec

(h) SPS Overlay – oblique view from inside at t = 0.65 sec

Figure 10 – Resultant Deflection Results from Bow Orthogonal Impact on Frame



(a) Steel



(b) SPS Overlay 20-30-Existing

Figure 11 – Internal Energy vs Time for Bow Orthogonal Impact on Frame

Influence Varying Kinetic Energy (Magnitude of the Impact)
Hull rupture did not occur for either the existing single hull steel FPSO or the FPSO with SPS Overlay for the design collision case of a 5000 tonne displacement OSV colliding with the specified FPSO at 2 m/s. The results from the analyses clearly indicate that SPS Overlay enhances impact protection by reducing deformations and equivalent plastic strains and by redistributing internal energy where the overlay plate absorbs a substantial portion of the impact energy. To quantify the increased energy absorption provided by SPS Overlay (amount of impact protection), the analyses were repeated with an increased impact velocity of 7.5 m/s (+155 MJ impact) to determine the energy and corresponding velocity that would cause the hull to rupture.

Additional analyses were conducted to determine whether the energy at rupture and equivalent plastic strains would be influenced by the increased strain-rate of the high velocity impact. Two collision analyses were compared, one with a velocity of 7.5 m/s and the other with a velocity of 2 m/s with mass increased to give equivalent kinetic energy. The results indicated that the increased strain-rate had no discernable (negligible) effect on the energy absorption to cause rupture as the high strain rate areas are highly localized as only a few elements out of tens of thousands that contribute to the total energy absorption capacity are affected.

The internal energy versus stern displacement is plotted in Figure 12 for the OSV stern oblique impact at the web frame of both the steel FPSO and the FPSO with SPS Overlay for the higher energy impact simulation. Hull ruptures for the FPSO with and without SPS Overlay are identified on the figure. Equivalent plastic strain at events a, b, c, and d, indicated on Figure 12 are shown in Figure 12. For the steel FPSO, hull rupture (a) occurs at 30.7 MJ, which corresponds to an equivalent velocity of 3.3 m/s or 6.4 knots. The strain contours for the FPSO with SPS Overlay that correspond to this energy, is shown in Figure 12(b). The maximum plastic stains are ~9%, well below fracture. For the FPSO with SPS Overlay, the existing hull and SPS Overlay plate rupture (d) occurs at 87.1 MJ and 97.1 MJ, respectively. The 97.1 MJ equates to a 5000 tonne OSV impacting the FPSO at a velocity of 5.9 m/s or 11.5 knots. SPS Overlay provides more than three times the energy absorption capacity of the existing steel FPSO before rupture occurs.

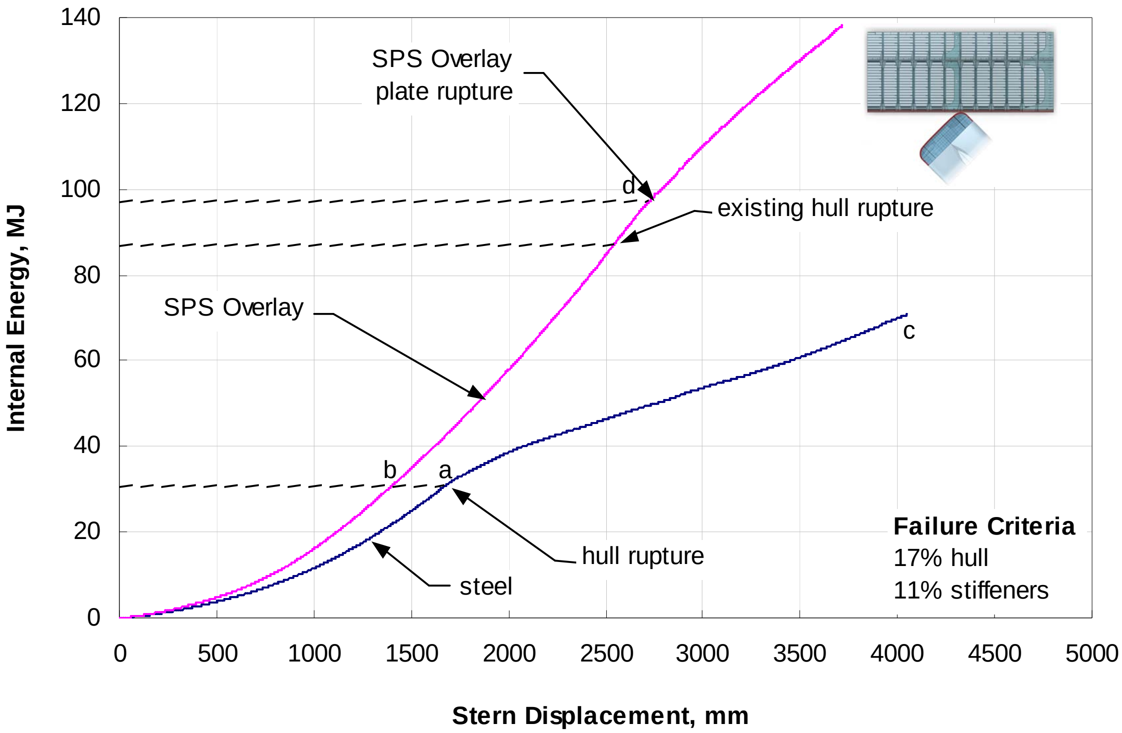
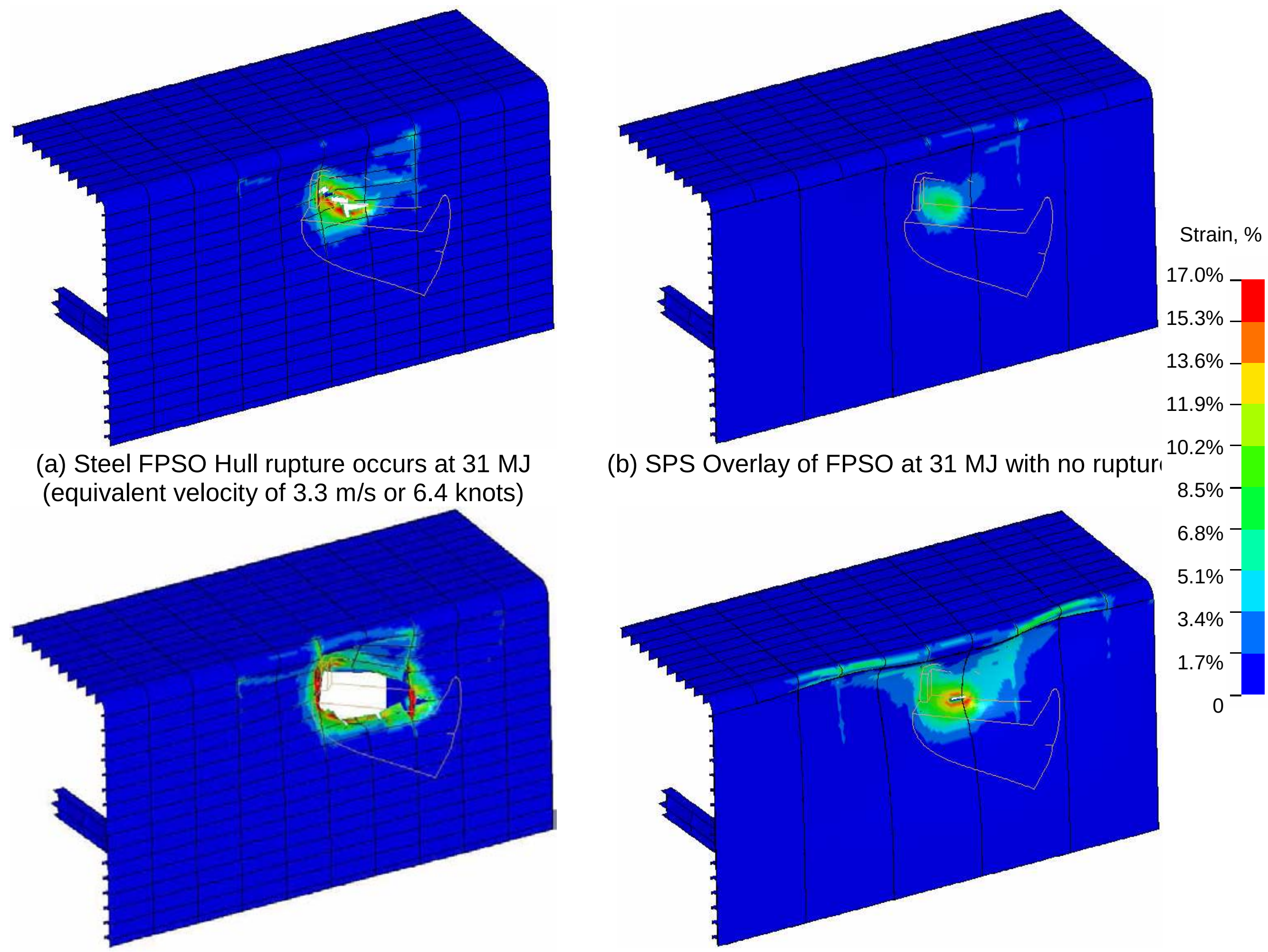


Figure 12 – OSV Stern collision on Steel FPSO with SPS Overlay



(a) Steel FPSO Hull rupture occurs at 31 MJ (equivalent velocity of 3.3 m/s or 6.4 knots)

(b) SPS Overlay of FPSO at 31 MJ with no ruptur

(c) Steel FPSO, 71 MJ

(d) SPS Overlay of FPSO starts to rupture at 97 MJ (velocity of 5.9 m/s or 11.5 knots)

Figure 12 – OSV Stern collision on Steel FPSO and FPSO with SPS Overlay

Table 5 lists the internal energies for each FPSO component at the impact energy that would cause hull rupture for the steel FPSO. With the SPS Overlay, the internal energy associated with the hull plating is shared between the existing hull and the SPS Overlay plate.

Table 6 compares the internal energies when rupture occurs for the hull of the FPSO with SPS Overlay to the original structure at rupture. With SPS installed, the SPS Overlay plate absorbs 37.5 MJ of energy enabling the FPSO to absorb 216% more energy before rupture occurs. As shown in Figures 13 (c) and (d) the area engaged in plastic deformation, resisting the collision, is greater for the SPS Overlay structure than the steel structure.

Similar analyses were conducted for the OSV bow perpendicular collision on a web frame, but because the OSV bow is soft, it collapses and absorbs the majority of energy associated with the impact. The FPSO hull remains intact (no rupture) at an impact energy of 155 MJ for both the original steel FPSO and the SPS Overlay.

Table 5 – Redistribution of Internal Energies at the Energy that Causes Steel Hull Rupture

	Time to Reach 30.7 MJ	Hull	SPS Overlay Plate	Elastomer	Web Frame	Stiffeners	Internal Energy
	ms	MJ	MJ	MJ	MJ	MJ	MJ
Steel	231.5	19.1	NA	NA	7.3	3.6	30.7
SPS Overlay	194.0	11.0	7.7	0.5	8.0	3.0	30.7
% difference	-16	-42	-	-	+10	-17	0

Table 6 – Internal Energies at Hull Rupture

	Time to Hull Rupture	Hull	SPS Overlay Plate	Elastomer	Web Frame	Stiffeners	Internal Energy
	ms	MJ	MJ	MJ	MJ	MJ	MJ
Steel	231.5	19.1	NA	NA	7.3	3.6	30.7
SPS Overlay	426.0	37.5	23.1	2.0	24.4	7.4	97.1
% difference	+84	+96	-	-	+234	+106	+216

Influence of Varying the Rupture Failure Criteria

The definition of the failure criteria is a function of the element type, element dimension (size) and thickness as it reflects the average straining over the element with a neck down region with higher strains at rupture. The preferred failure of 17% for the hull plating and 11% for the stiffeners, Lehmann et al. (2001), is based on measurements from collision events. Other failure strain criteria such as that proposed McDermott (1974), which specify the failure strain as a function of rupture strains obtained from tensile tests, as given by Equation 2 may also be used.

$$\varepsilon_b = 0.10(\varepsilon_f / 0.32) \qquad (2)$$

where,

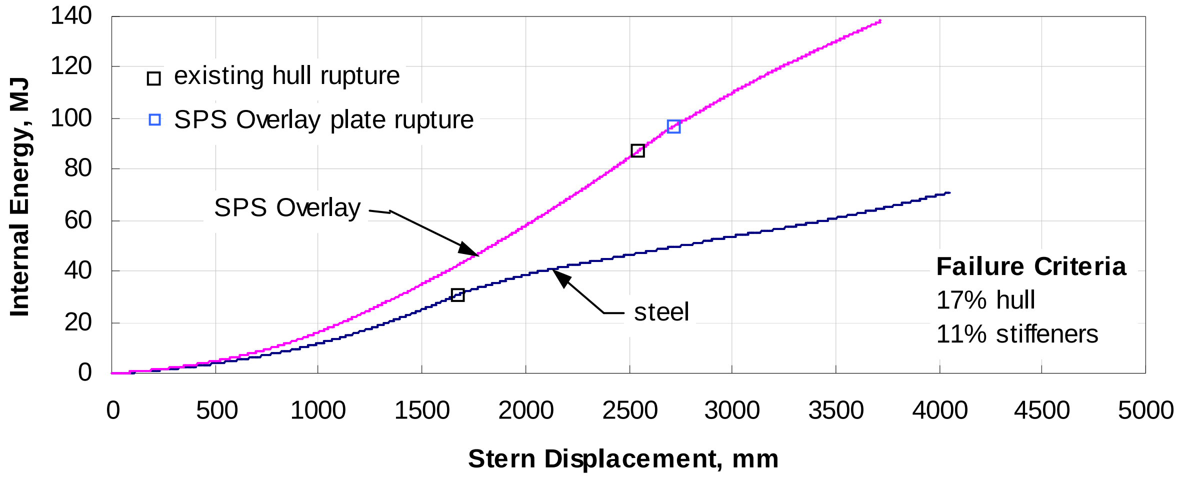
ϵ_f = failure strain from tensile tests, 0.45

The following failure criteria were investigated to determine this criterions influence on the energy absorption capacity at rupture for both structural configurations. The lower bound criteria cited is unlikely and has no scientific basis other than this criterion would provide a lower bound solution.

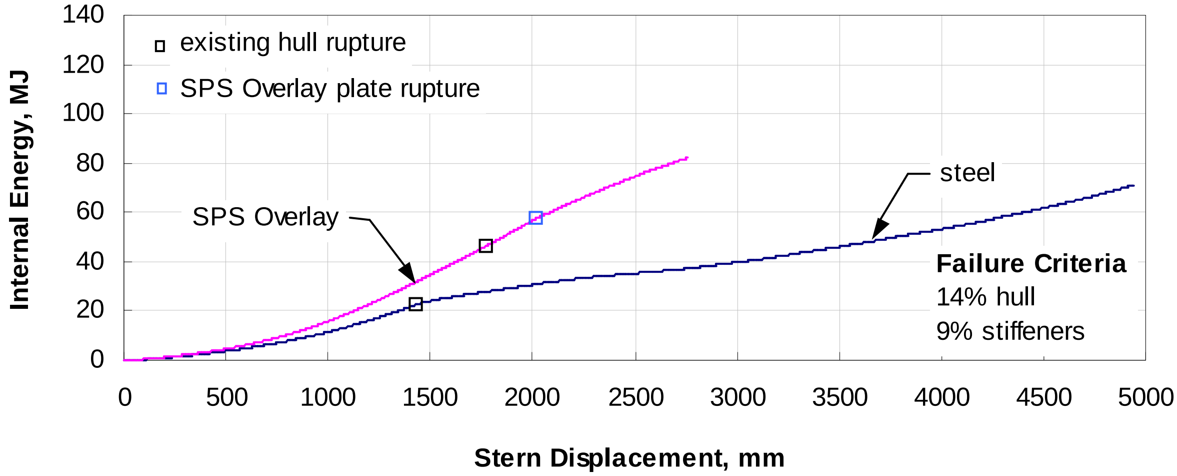
- **Lehmann failure criteria:** 17% for the hull and 11% for the longitudinal stiffeners, Lehmann et al. (2001) – *most probable and based on data from existing collision and grounding events*
- **McDermott failure criteria:** 14% for the hull and 9% for the longitudinal stiffeners, McDermott (1974) - *historic failure criteria used is collision simulations*
- **lower bound failure criteria:** 10% for the hull and 8% for the longitudinal stiffeners

A summary of the internal energies when hull rupture occurs for the stern and bow impacts for these failure criteria is given in Table 7. Note that as the failure strain criteria are reduced, the ratio of the energy required to rupture the hull of the FPSO with SPS Overlay to that of the original FPSO also reduces. For the OSV stern impact, SPS Overlay offers 3.2, 2.5, and 2.0 times excess energy absorption capacity for the Lehmann, McDermott, and lower bound failure criteria, respectively. Figures 13 and 14 illustrate the internal energy versus stern displacement curves for the stern impact at each failure strain criteria. Hull rupture is indicated on the graphs.

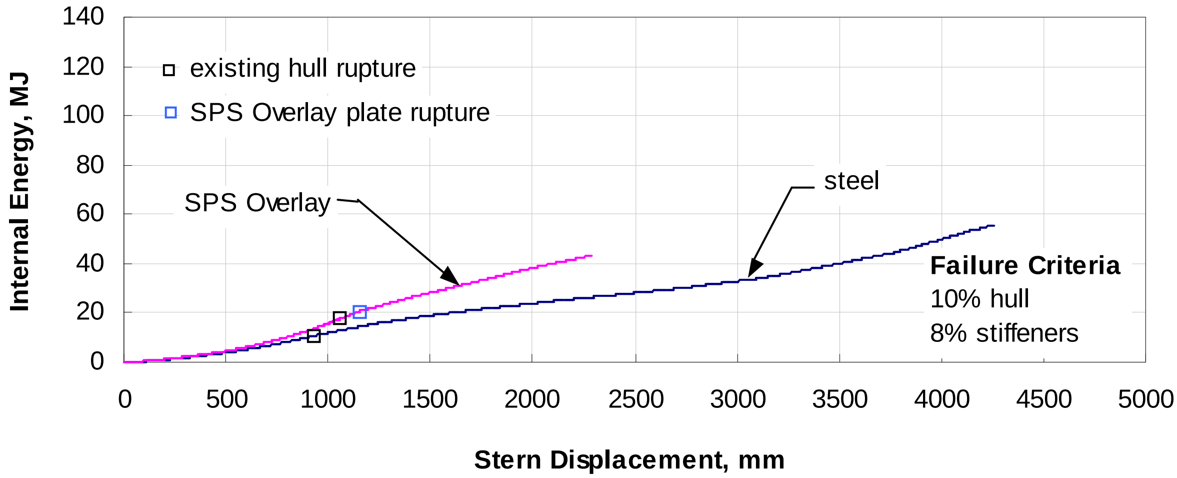
For the OSV bow impact with the Lehmann failure criteria, for the 7.5 m/s collision 155 MJ impact hull rupture could not be initiated for either structure, as the bow collapses, plastically deforms and absorbs the majority (~67%) of the impact energy. For the bow impact with the lower bound failure criteria, hull rupture occurs at 45 MJ and 141 MJ for the steel FPSO and FPSO with SPS Overlay, respectively. Figure 15 shows the internal energy vs. bow displacement curve for the bow for the analyses conducted with the lower bound failure criteria, where displacement is the rigid body motion of the bow away from the deformed structure. As a result, the energy-displacement curves in Figure 15 exhibit similar displacement responses. For the lower bound failure criteria, SPS Overlay provides 3.1 times more energy absorption capacity (141 MJ total). The corresponding curves for the Lehmann failure criteria are not included because they do not indicate any hull rupture.



(a) Lehmann (2001) failure criteria

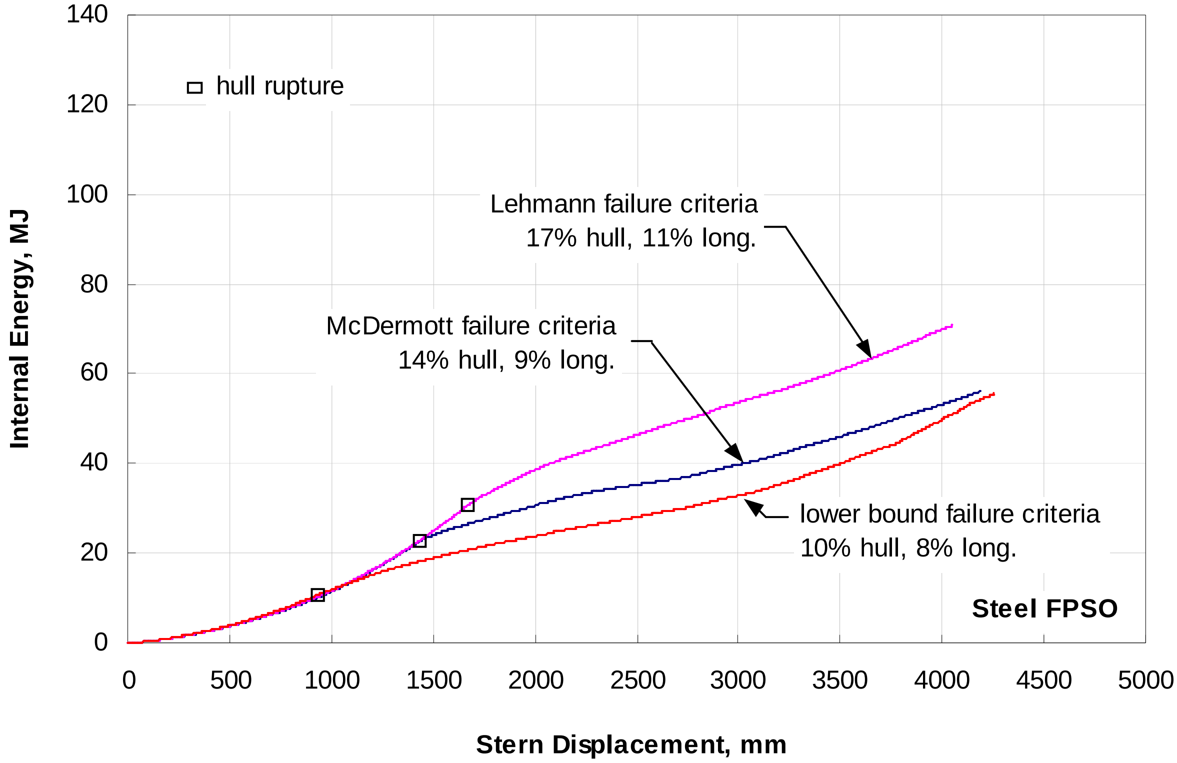


(b) McDermott (1974) failure criteria

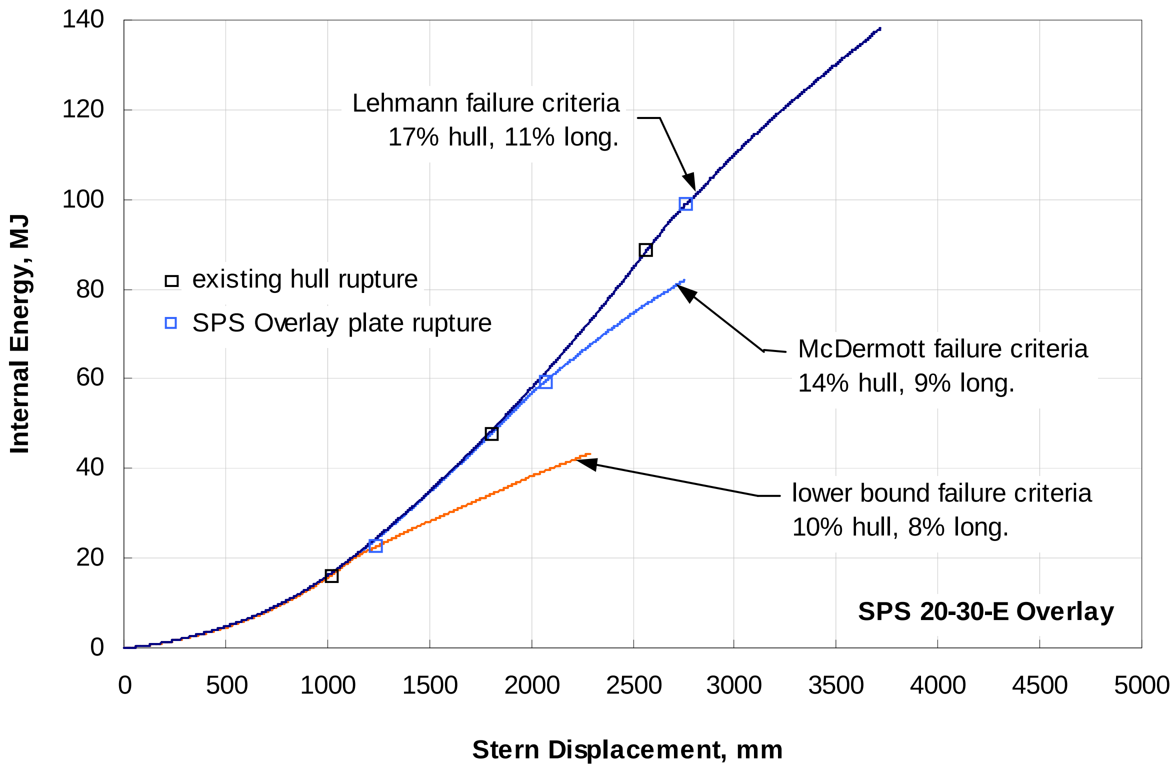


(c) lower bound failure criteria

Figure 13 – Internal Energy - Displacement Curves for Stern Impact at Various Failure Criteria



(a) Steel



(b) SPS Overlay

Figure 14 – Internal Energy - Displacement Curves for Stern Impact at Various Failure Criteria

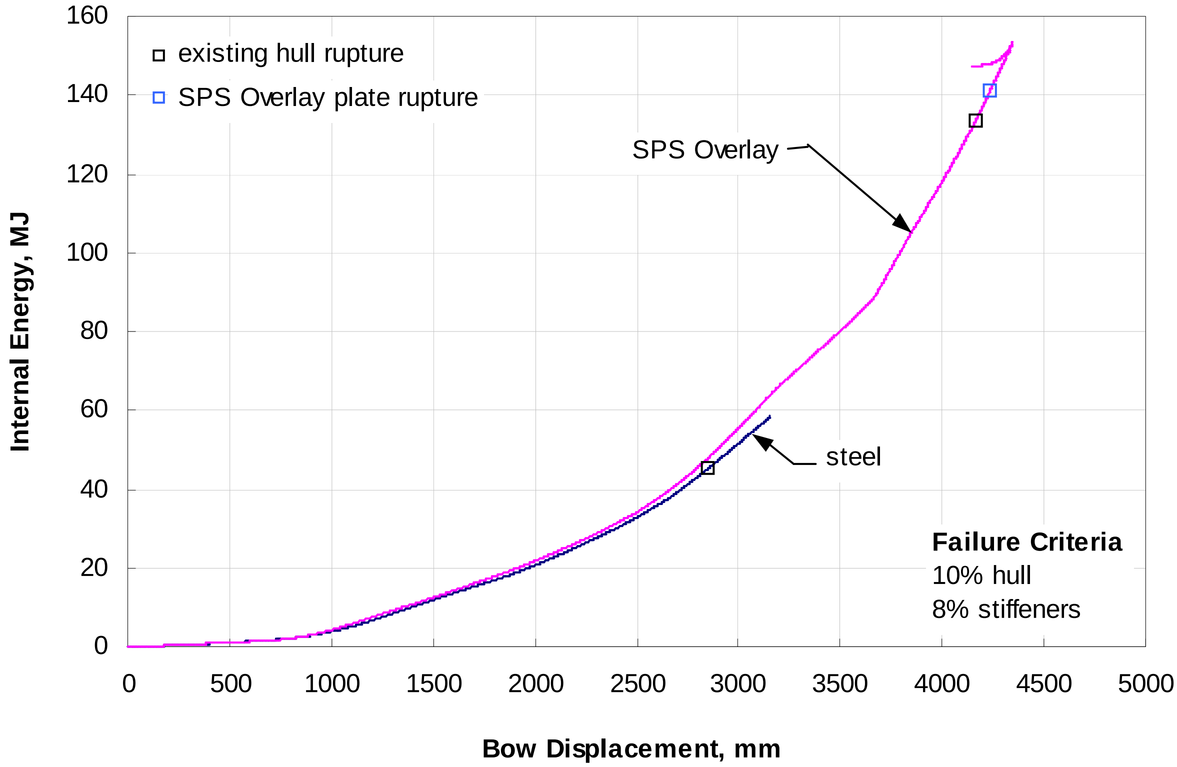


Figure 15 – Internal Energy - Displacement Curves for Bow Impact at Lower Bound Failure Criteria

Table 7 – Internal Energy at Hull Rupture for Various Failure Strain Criteria

	OSV Stern Impact			OSV Bow Impact	
	Lehmann 17% hull 11% long.	McDermott 14% hull 9% long.	Lower bound 10% hull 8% long.	Lehmann 17% hull 11% long.	Lower bound 10% hull 8% long.
	MJ	MJ	MJ	MJ	MJ
Steel	30.7	22.6	10.7	> 155[a]	45.3
SPS Overlay (inside hull)	87.1	46.4	15.2	> 155[a]	133.4
SPS Overlay (Overlay plate)	97.1	57.4	21.1	> 155[a]	141.0
% difference (based on hull plate rupture)	+216	+154	+97	-	+211

a. no rupture at maximum applied energy of 155 MJ.

Comparison of the Energy Absorption of a FPSO with SPS Overlay and a FPSO Fitted with a Sponson

This section explores the relative energy absorption capacity between an SPS Overlay solution and those current solutions with added side shell collision protection provided by a second hull separated by a void space, that take the form of either a cofferdam fitted internally or an external sponson, as shown for the latter in Figure 16. In either case, the structure locally provides a double hull type construction with the spacing between the hulls of either 2000 mm or 3000 mm. It is anticipated that the internal cofferdam or sponson would be constructed with plate and stiffener scantlings similar to the existing FPSO hull.

The energy absorption capacity of a current typical option of an FPSO fitted with a sponson was determined by a numerical simulation for an OSV stern impact at an oblique angle to the sponson web frame with the same analytical conditions and failure criteria as the previous simulations for a FPSO with an SPS Overlay. The equivalent plastic strain failure criteria (Lehmann, 2001) of 17% was applied to both the existing hull and the sponson plating and the 11% was applied to all longitudinal stiffeners since the element sizes and plate thicknesses are similar. The collision speed for the OSV was 7.5 m/s or 14.6 knots. Note that the bow analysis was not conducted as it was previously demonstrated that the majority of the impact energy is absorbed by the bow and that it was not critical load case.

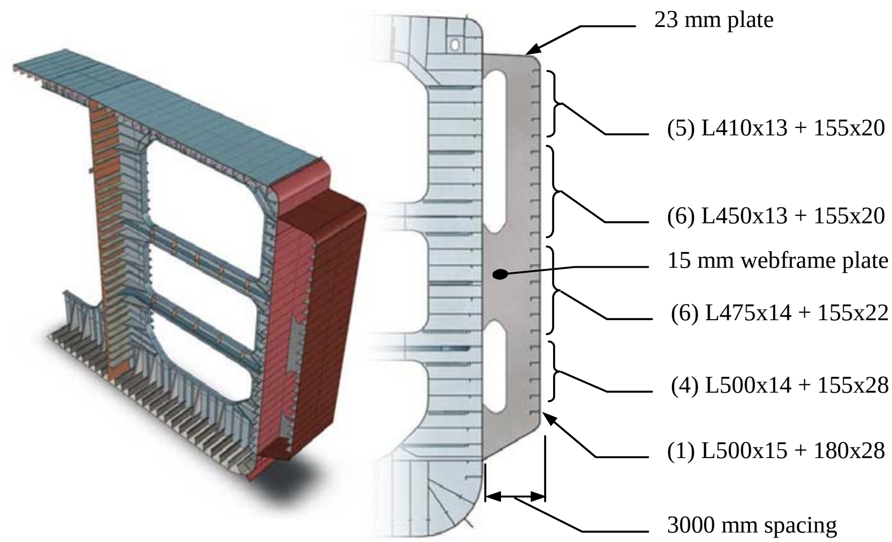


Figure 16 - Sponson Description

The internal energy versus resultant stern displacement is plotted in Figure 17 for the OSV stern oblique impact at the web frame for the single side-shell FPSO, FPSO with sponson, and the FPSO with SPS 20-30-exisitng Overlay. The energy associated with hull rupture are also indicated on Figure 17 by the red dots with the internal absorbed energy for each of the above structural configurations being 31 MJ, 127 MJ, and 97 MJ, respectively.

The energy absorption capability of the SPS Overlay can be readily modified by simply changing the thickness of the Overlay plate, where the energy absorption capacity is directly proportional to the volume of steel being plastically deformed Minorsky (1959). By increasing the thickness of the SPS Overlay plate to 30 mm, the volume of hull plate being engaged in the collision event increase by the ratio of the total hull plate thicknesses, 51.5 mm / 41.5 mm, or a ratio of 1.24 times. The results of the numerical simulation of the same OSV stern impact on an FPSO with SPS 30-30-existing Overlay are shown in Figure 17, with hull plate rupture occurring at 120 MJ of internal absorbed energy.

The SPS Overlay solution provides 94% of energy absorption capacity offered by the FPSO with sponson protection. There are practical limits to increasing plate thicknesses associated with weight, constructability and welding.

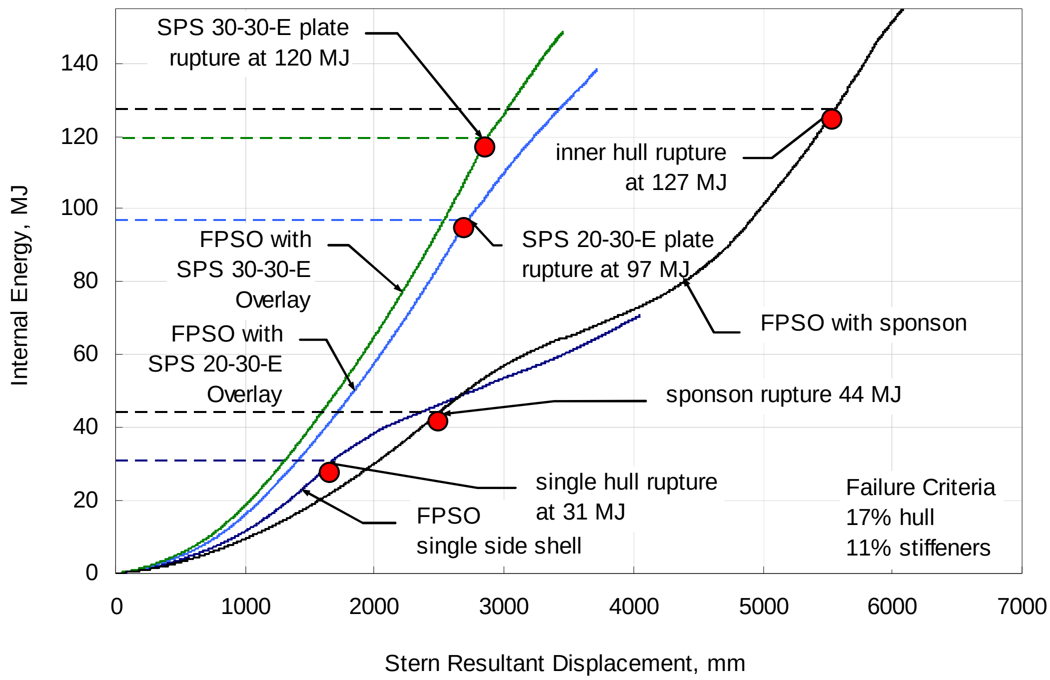


Figure 17 - Energy vs Stern displacement for FPSO (single side-shell), FPSO with SPS Overlay, and a FPSO with a Sponson

Tables 8 and 9 summarize the distribution of internal energy when the sponson hull plate ruptures (44 MJ) and when the hull structure is finally breached. Figures 19 and 20 illustrate the deformed shape of the hull structures and the equivalent plastic stain energy distributions at the same load levels.

Sponson Rupture (44 MJ), Figures 19 (a,b), 20 (a,b)
With respect to the sponson solution, the sponson acts independently of the existing hull structure in absorbing the collision energy, absorbing 97% of the total internal energy at that time in the collision event. There is significant wide spread deformation of the sponson over three transverse frames with concentrated plastic straining between two frames. The ruptured structure will have multiple tears or sharp cracks in and around hard spots, each of which will readily propagate at lower energy levels than that required to plastically deform the steel. The analyses does not model crack propagation, hence the remainder of the solution represents an upper bound to total energy absorption capacity.

At the same energy level, the maximum deformation in the SPS Overlay is less, the maximum equivalent plastic strain in the hull plating is well below the fracture limit (~10%), and the bulk of the internal energy is being equally shared by the existing hull, the SPS Overlay plate and by one transverse web frames.

Table 8 – Distribution of Internal Energy at Rupture of the Sponson Hull Plate

	Time	Sponson Plate	Sponson Web Frame	Sponson Stiffeners	FPSO Hull	SPS Overlay Plate	Elastomer	FPSO Web Frame	FPSO Stiffeners	Total Internal Energy
	Ms	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ
Sponson (rupture)	353	23.8	10.8	8.1	0.1	NA	NA	0.5	0.0	44.0
SPS Overlay (no rupture)	224	NA	NA	NA	13.9	12.9	0.8	11.8	3.7	44.0

Final Hull Breach (127 MJ / 120 MJ), Figures 19 (c,d), 20(c,d)
With respect to the sponson solution, a significant portion of the increased absorbed energy over that where the sponson was initially breached, 44.0 MJ, is absorbed by the ruptured sponson, +24 MJ in the sponson hull plate and a further +18.5 MJ in the transverse web frames. The contribution from these parts of the structure to the total energy absorption capacity of 127 MJ is unlikely as previously described and this value represents an upper

bound. At final breach, the energy absorption contribution of the existing FPSO hull is only 23.1 MJ, hence the probable range of energy absorption is from a low of 67.1 MJ (not likely) to a high of 127 MJ. At final hull breach the void space is flooded and the rupture in the sponson is extensive with a length of approximately 8000+ mm.

In comparison, the SPS Overlay shows a uniformly distributed deflected shape extending laterally over four transverse frames and upwards into the gunwale and deck. The equivalent plastic strains in and around the point of contact are generally low, less than ~7%, except at the point of rupture at / or near the hull plate transverse frame intersection. Because of the relative stiffness of the composite SPS hull plate, a significant amount of energy is being absorbed by the gunwale and once again the bulk of the absorbed energy is being absorbed by the composite SPS plates (65% of the total energy), virtually equally between the existing hull plate and the SPS Overlay plate. Not reflected in these calculations is the inherent local puncture resistance of SPS plating, hence any sharp objects or broken brackets that may puncture a single steel plate and curtail the energy absorption capacity of the structure are less likely to occur for the SPS Overlay solution.

Notwithstanding, the SPS Overlay solution with a 20 mm overlay plate provides 97.1 MJ of energy absorption capacity, 8.8 times that required by IMO MEPC/Circ 406 and the 30 mm overlay plate 10.9 times the required capacity.

Table 9 – Distribution of Internal Energy at Rupture of the Hull Plate

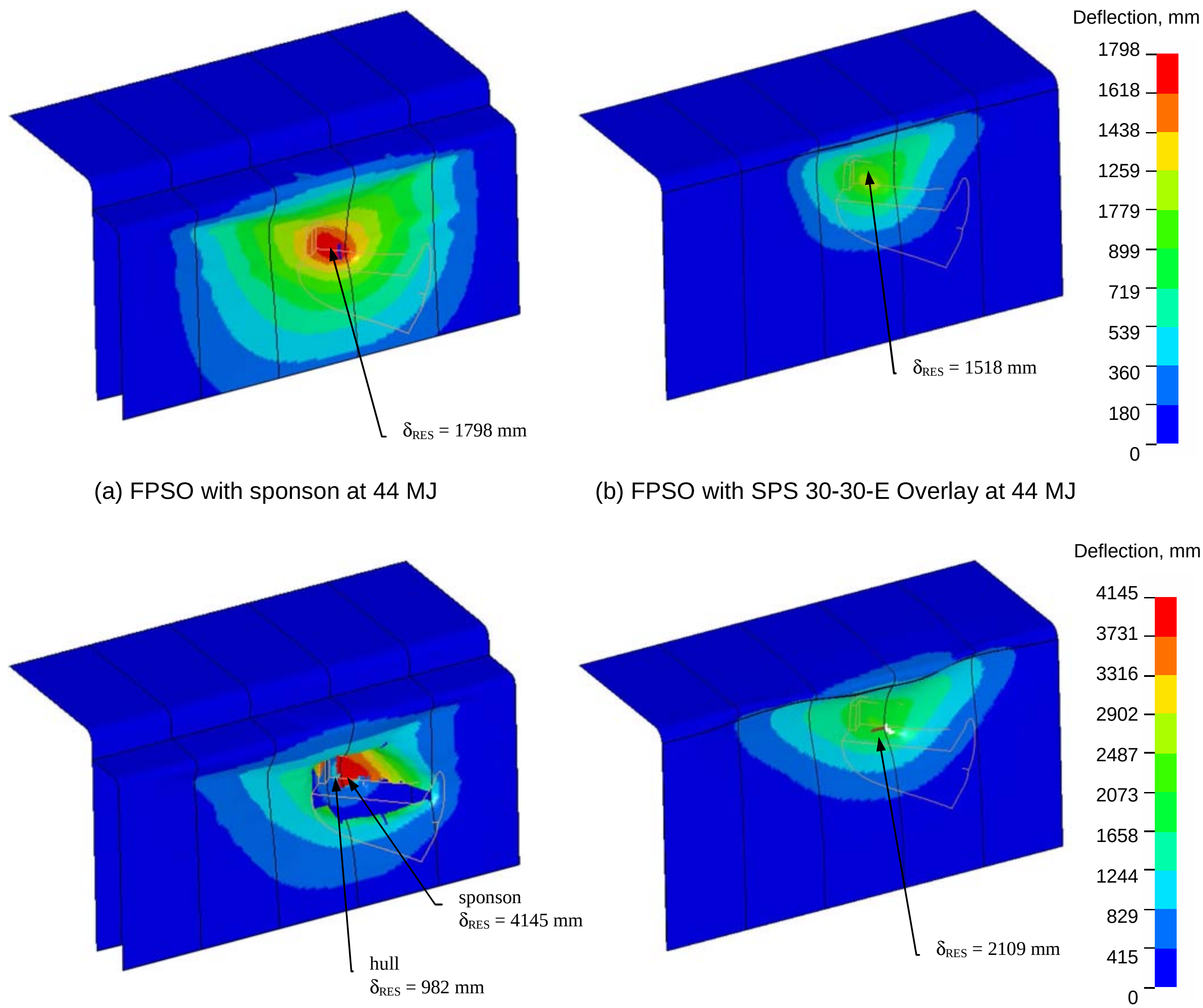
	Time	Sponson Plate	Sponson Web Frame	Sponson Stiffeners	FPSO Hull	SPS Overlay Plate	Elastomer	FPSO Web Frame	FPSO Stiffeners	Total Internal Energy
	ms	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ
Sponson	952	47.8	29.3	12.9	14.0	NA	NA	5.1	4.0	127
SPS Overlay	481	NA	NA	NA	41.9	35.5	2.4	29.1	8.2	120

Additional Risk Benefits

Once it was established that the use of a SPS Overlay solution for fendering on an FPSO not only meets but exceeds the low energy collision impact requirements of MEPC/Circ 406, SBM conducted a comparative study of current solutions (the use of either cofferdams or sponsons) and SPS Overlay; and found the SPS Overlay solution to be both commercially viable and advantageous to shipyards by reducing the work and risk associated with this element of an FPSO conversion.

In addition, it was also determined that the SPS Overlay solution presented a broader package of reduced risk benefits for the owner, shipyard and Class Societies that have been identified and where possible quantified, including;

- superior puncture resistance,
- a more robust side shell that is designed to sustain routine in service impacts without detrimental effects,
- a construction that strengthens the side shell and reduces critical fatigue stresses,
- a simplified solution that minimizes on going maintenance and eliminates the need for expensive tank coatings, de-humidifiers, vent and sounding pipes, and bilge eductors, and
- eliminates 40 void space inspections, 2880 man-hours per void space over a twenty year period.



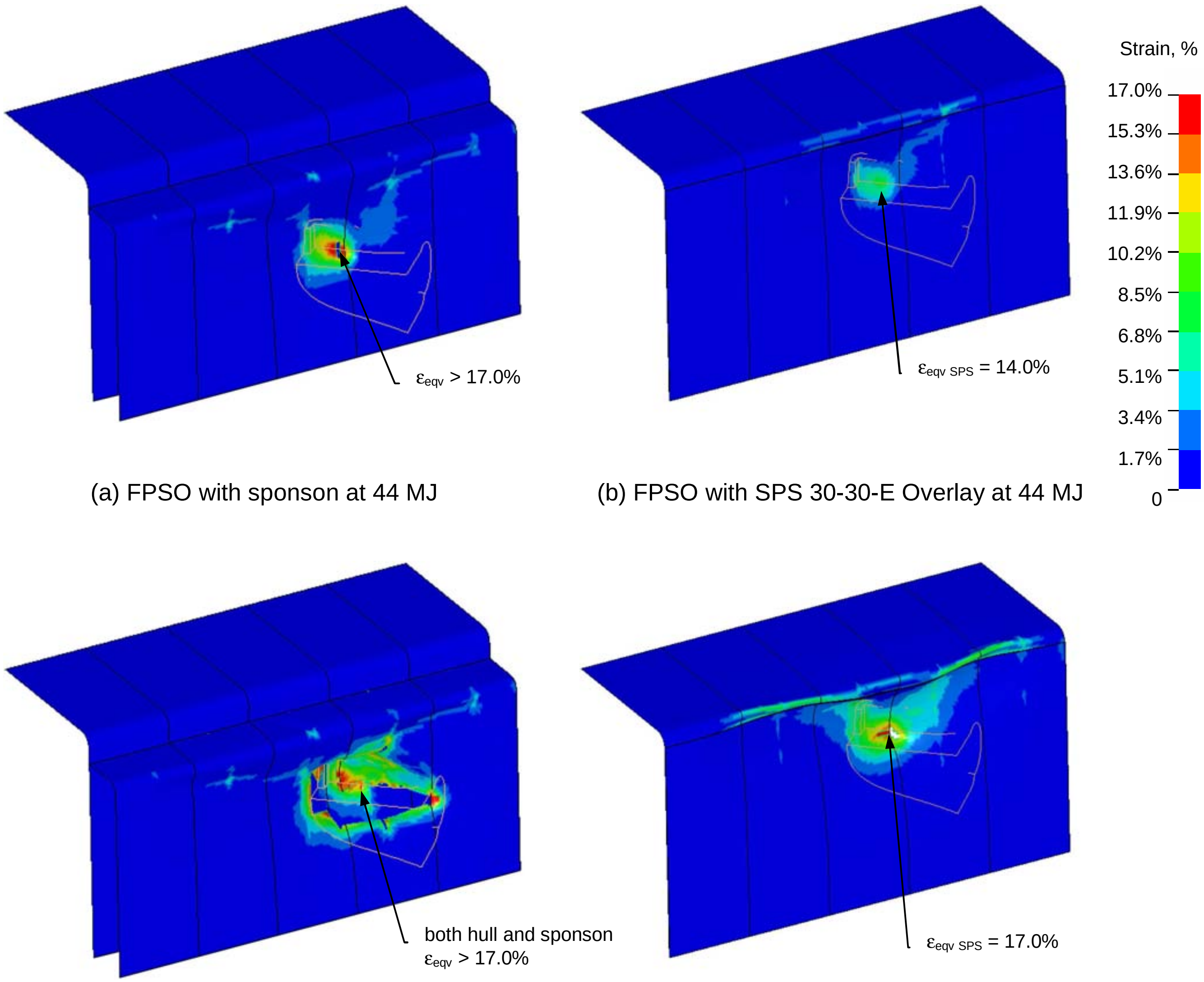
(a) FPSO with sponson at 44 MJ

(b) FPSO with SPS 30-30-E Overlay at 44 MJ

(c) FPSO with sponson at hull rupture initiation at 127 MJ

(d) FPSO with SPS 30-30-E Overlay at hull rupture initiation at 120 MJ

Figure 18 – Resultant Deflection



(a) FPSO with sponson at 44 MJ (b) FPSO with SPS 30-30-E Overlay at 44 MJ

(c) FPSO with sponson at hull rupture initiation at 127 MJ (d) FPSO with SPS 30-30-E Overlay at hull rupture initiation at 120 MJ

Figure 19 – Equivalent Plastic Strain

Conclusions from Engineering Study

Based on the results from the analyses the following conclusions can be made;

- Use of SPS Overlay as fendering on an FPSO not only meets, but exceeds the requirements of MEPC/Circ 406 "Guidelines for Application of MARPOL Annex I Requirements to FPSOs and FSUs".
- SPS Overlay will provide an impact resistant hull structure that will be able to withstand the design collision case of a 5000 tonne displacement OSV colliding with the specified FPSO at 2m/s without rupture.
- SPS Overlay provides a significant increase in local impact resistance, 1.4 times for blunt objects to 8.5 times for sharp objects close to stiff elements, over that of the existing steel hull plate, providing capacity to prevent local puncture from ruptured brackets, stiffeners or frames during the collision event or from sharp objects that may be located on the outside of the OSV that were not explicitly modeled.
- The faceplate of the SPS 20-30-existing Overlay absorbs almost an equal amount of energy as the existing hull plate.
- The SPS Overlay structure provides ~3.2 times more capacity than the existing FPSO hull structure for the OSV stern oblique impact on the FPSO web frame.
- The equivalent plastic strain in the SPS Overlay faceplate is less than half of that in the existing hull plate.

The existing hull plate ruptures first followed by the SPS Overlay faceplate. The reduction is equivalent plastic strain for the steel FPSO with SPS Overlay over the existing FPSO indicates that there is substantially more energy absorption capacity not yet utilized.

- The connection of the SPS Overlay faceplate to the existing hull structure have been detailed to isolate cracks from the existing structure from propagating into the faceplate thereby providing a redundant secondary steel barrier that prevents oil outflow and additional energy absorption capacity.
- SPS Overlay 30-30-existing provides impact resistance similar to that of a sponson, but offers substantial ease of construction and reduction in complexity, while maintaining similar design dimensions and therefore similar operating hydrodynamics.
- The energy absorption capacity of the sponson is an upper bound estimate.
- At low speed impacts, the sponson would sustain greater damage than the SPS Overlay because the SPS engages a larger area of plate. The damaged sponson areas may see strains close to rupture, which would reduce the survivability of this plating in subsequent collision events. Once the sponson plating is permanently deformed, this area may be more susceptible to local damage such as crack propagation due to fatigue.
- The SPS Overlay solution was found to be both commercially viable and advantageous to shipyards by reducing the work and risk associated with this element of an FPSO conversion.
- SPS Overlay solution presented a broader package of reduced risk benefits for the owner, shipyard and class societies including, superior puncture resistance, robust side shell, reduced critical fatigue stresses, simplified maintenance, and the elimination void space inspections.

SPS Overlay Fendering Projects

The successful completion of the engineering studies and approval in principle by the Classification Societies ABS, LR and DnV allowed SBM to pursue first implementation of SPS Overlay in lieu of cofferdams on their ABS classed FPSO P-57 for Petrobras. An SPS Overlay comprising a 15 mm thick exterior SPS plate and a 30 mm elastomer core combined with the 19 mm thick existing shell plating of the very large crude carrier MT ACCORD which was the conversion vessel was used. The structural arrangement of the ACCORD was very similar to that of the FPSO candidate vessel used in the collision study. The SPS Overlay scantlings, in combination with the existing structural framing were estimated to provide 76 MJ of energy absorption capability (Bond, 2008). The energy absorption estimation was an extrapolation of the data and results of the large collision study, reported above, and is primarily based on the fact that the amount of energy absorbed is directly proportional to the volume of steel plastified during the collision event.

The FPSO P-57 SPS Overlay installation process steps included (1) preparation of the existing plating surface to remove all paint and surface rust, cleaning to a standard of SA2.5 while simultaneously roughening the surface to 60μm; (2) welding perimeter bars to the existing plate, with radius corner tapered bars used at the transition from SPS to the existing hull at the boundary of the area being protected; (3) welding the new SPS plate to the perimeter bars (surface of new plate prepared as for the existing shell plating on the face that is interior to the cavity); (4) creation of injection ports for the elastomer and vent holes for the air that will be forced from the cavity by the elastomer; (5) elastomer injection in multiple vertical lifts and (6) sealing of injection and vent holes with welded steel plugs.

Figure 20 shows the SPS installation steps undertaken on the P-57, between January and April 2009, at Keppel, Singapore. A total of 96 cavities were injected covering 3111 m^2 of the side shell with the SPS protective layer.

In November 2009, an SPS Overlay 16(AH36)-30-e was installed on Modec's ABS classed FPSO CIDADE DE ANGRA DOS REIS MV22. The existing shell plate thickness on the tanker being converted was 16 mm. A total of 34 cavities were injected, between 30 October and 14 November, covering 1126 m^2 of the side shell with the SPS protective layer at Cosco Dalian, China.

In May 2010, an SPS Overlay 15(EH36)-30-e was installed on the DnV classed Petrobras FPSO P-58. The existing shell plate thickness on the tanker being converted was 16 mm. A total of 56 cavities were injected covering 1518 m^2 of the side shell with the SPS protective layer at Keppel, Singapore.

In August 2010, an SPS Overlay 15(AH32)-30-e was installed on SBM's ABS classed FPSO ASENG. The existing shell plate thickness on the converted tanker BAUHINIA was 19 mm. A total of 64 cavities were injected covering 2121 m^2 of the side shell with the SPS protective layer at Keppel, Singapore.

Surface Prep

Tapered edge perimeter bar, radius corner

Plate Installation

Elastomer Injection

Figure 20 – SPS Installation FPSO P-57

Summary

The Sandwich Plate System (SPS) in the form of a compact double hull (CDH) can offer equivalent protection to either an internal cofferdam or external sponson for the prescribed impact between an offshore supply vessel and the FPSO in way of the boat landing area to meet and exceed the requirements of MEPC/Circ 406 “Guidelines for Application of MARPOL Annex I Requirements to FPSOs and FSUs”. In addition, the SPS CDH provides a package of risk reduction benefits over that of cofferdams and sponsons that include; a significant increase in local impact resistance, a strengthened side shell that reduces critical fatigue stresses, schedule reduction for fabrication and installation, reduced risks during fabrication, less maintenance and eliminates the risks and costs for through life void space inspections.

SPS CDH installed on projects completed to date including the FPSOs P57, P58, MV22 and Aseng.

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