EFFICIENT NON-LINEAR DYNAMIC ANALYSIS OF ELEVATED JACK-UPS UNDER VESSEL IMPACT

A. Raithatha*, R. W. P. Stonor
Noble Denton Marine Assurance and Advisory (ND)
DNV GL – Oil & Gas

** corresponding author: ankor.raithatha@dnvgl.com*

ABSTRACT
In December 1996, an impact from a pipe-lay barge caused damage to the starboard leg of the jack-up "Harvey H. Ward" in the Tapti Field offshore Mumbai, India. A 1997 Jack-Up Platform conference paper describing the post-incident recovery operations explains that initial attempts at elasto-plastic collapse modelling made at the time of the incident to predict the observed deformation yielded inconclusive results. In recent years, ND have adopted such non-linear dynamic elasto-plastic collapse finite element analysis (FEA) methods as their standard analytical tool for vessel impact assessments for jack-up structures, typically for clients preparing safety cases for relevant authorities (e.g. UK HSE). This paper describes a vessel impact analysis of the Harvey H. Ward incident undertaken by ND using their current assessment method. The model is efficiently developed using an in-house JUSTAS-to-Abaqus software converter tool together with modern non-linear dynamic FEA commercial software and runs on a standard modern desktop computer. The form of the damage characteristics predicted by the FEA model compare very well against the observed damage profile of the 1996 incident, providing confidence in the analysis approach and an opportunity to reflect upon the progress that has now made this method suitable for engineering consultancy scale analysis work.

KEY WORDS: jack-up, vessel impact analysis, elasto-plastic, finite element, safety authority, Abaqus, leg damage.

INTRODUCTION

The Noble Denton Marine Assurance and Advisory (ND) service area of DNV GL – Oil & Gas have received many requests over the years to assess the capability of elevated jack-up structures to withstand a vessel impact. The purpose of such assessments is typically for the rig operator to satisfy themselves, the field operator or governing local safety authority that vessel impact risks have been considered to an industry accepted standard. In such cases the jack-up rig has typically already been built and may be in operation, leaving little scope to undertake structural modification and little appetite by the rig owner to fund an extensive analysis project.

There are numerous approaches to performing jack-up leg impact analysis, ranging from simplified hand calculations using elastic and elastic-plastic analysis principles along with 'code-based' structural strength checks, to more sophisticated non-linear dynamic finite-element analysis (FEA). Suitable software tools for the latter have been available for many years but due to the perceived complexity and the time-consuming nature of performing the analysis, post-processing the output and interpreting the results, they tend to be reserved for larger scale research-type projects. Engineering consultants employed on short-term vessel impact analysis projects, perhaps faced with clients aiming for a quick 'tick-box' analysis calculation, have tended to persist with the simpler jack-up leg impact analysis methods, which carry reduced risks with regards to the potential for project over-runs and the associated commercial consequences, and a greater certainty in the sense that pass/fail limiting criteria can be clearly documented and referenced against industry standard practices and literature.

Although such simplified calculations may be justified for some jack-up leg designs, they are also conservative and can become unwieldy if the basic limiting criteria are exceeded. The ship impact section of DNV RP-C104 (Ref.[7]) continues to recommend a simplified 2 degree of freedom jack-up leg impact analysis method but it also acknowledges that if stresses are found to exceed the elastic limit using the simplified approach the calculations should be reworked based on non-linear methods that *"account for formation of plastic hinges and* *buckling of compression members"*; such situations are met more often than not in the authors experience. A comprehensive Master's thesis on jack-up vessel impact analysis, Ref. [9], provides an evaluation of a simplified analysis method that was used by a jack-up design house; it concludes with recommending that the method be replaced by a more sophisticated non-linear dynamic FEA approach detailed in the thesis. Interestingly, the recommendation was made not only to reduce conservatism in the structural design of the impacted leg, but also because the study found the simpler approach can under-represent structural integrity risks associated with the global response of the jack-up. Another useful paper, Ref. [5], provides a comparison of various approaches to vessel impact analysis of varying complexity.

In summary, non-linear dynamic FEA is a preferred approach but it can also be viewed as a last resort by engineering consultants, to be attempted when there is a need to strip away conservatisms inherent in simpler methods. This paper aims to challenge that perception. With continued progress on the capabilities of desktop computers, commercial FE analysis software packages (in this case Abaqus) and improved guidance literature for non-linear FEA (e.g., DNV-RP-C208, Ref. [1]), the nonlinear dynamic FEA approach has now been observed to be: as time-efficient as the simpler analysis methods previously employed by ND; reliable in terms of generating plausible results; and straightforward to document against references to industry accepted standards. It also possesses the advantage that the damaged rig generated as a result of the impact can be used directly in studies to show the level of subsequent environmental loading that the damaged unit can withstand.

This paper is structured as follows: an overview of ND's current jack-up leg impact analysis implementation is provided, followed by details on various aspects of the implementation. After a brief recap of the damage observed in the Harvey Ward 1996 incident as presented at the 1997 Jack-up Platform Conference (Ref. [6]), some results from the current analysis are detailed. It is demonstrated that the analysis has captured all of the key damage characteristics that were observed in the 1996 incident.

BASIC SUMMARY OF THE NON-LINEAR DYNAMIC FEA IMPLEMENTATION

ND's current approach to non-linear dynamic FEA for jack-up vessel impact analysis is primarily based on guidance provided in Ref. [1] and it includes the following features:

1. Use an in-house Python-scripted tool to build an Abaqus 3-leg model of a jack-up directly from its data file for the JUSTAS (Site-specific Analysis) software program.
2. For the first run, set spudcan boundary conditions to be rotationally fixed.
3. Define leg structure material properties using a bi-linear elasto-plastic constitutive relationship to capture yield.
4. Introduce initial geometric imperfections in chords and braces to facilitate buckling of slender elements.
5. Perform tests on local models of chord and brace elements to ensure:
    - the applied so-called equivalent imperfections induce buckling at axial load levels that are consistent with what would be expected from code-based strength checks (e.g. ISO 19905-1:2012, Ref [8]),
    - plastic hinge formation occurs at the expected plastic moment capacity of the section.
6. Transfer vessel loading to the structure by means of a standard 'ship' mass and non-linear elastic spring model to represent energy absorbed by crushing of the vessel. The normal techniques of increasing ship mass to account for added-mass is used.
7. The overall leg chord/brace structural integrity is determined directly if equilibrium is maintained at the end of the vessel impact load despite local damage being observed. Further checks on forces at holding system level and footings are performed against relevant limiting criteria.
8. If structural integrity is maintained, to meet UK HSE policy or DNV RP-C104 requirements, the structure is further subjected to wind-wave-current storm loads representative of (typically) a 1-year event, to check that although damaged, the structure has retained an acceptable level of reserve capacity (e.g. to allow safe de-manning after the impact).

9. Repeat above with further load cases to test impact at different loading directions, different chords, different impact heights along the leg, and leg length below the keel.
10. If all the above is acceptable, repeat with pinned spudcan rotational fixities. The pinned condition is usually expected to be less onerous, as it allows more compliance in the structure. Hence more of the overall impact energy can be absorbed by causing global sway of the jack-up and redistribution of loading to non-impacted legs. For location-specific analyses non-linear spudcan/soils models can be included directly into the model to replace the range of conditions considered by the fixed/pinned simplification for the foundations.

In past attempts at implementing non-linear FE vessel impact analyses the results were found to yield unexpected damage profiles that were difficult to explain. Introducing brace imperfections as per step 4 above was a key improvement that helped to resolve this issue. Item 1 above has also been instrumental in improving speed and reducing human errors in the model generation process.

DETAILS OF THE FEA MODEL

JUSTAS is a jack-up modelling and analysis software that ND uses extensively to represent the structural characteristics of jack-up platforms that are being studied. JUSTAS can represent braced leg structures efficiently with a few lines of data. The Abaqus finite element analysis model of the Harvey Ward jack-up shown in Figure 1 was developed using an in-house JUSTAS-to-Abaqus converter tool, which reads information from an existing JUSTAS rig model of a jack-up (in this case the Harvey Ward), along with a range of user-defined parameters to output a model with the following features:

- Trussed legs are spaced and oriented as defined in JUSTAS, with further input parameters to control offsets between brace nodes and the number of finite elements to be used along the length of each leg scantling. Different leg penetrations can be defined for each leg of the jack-up if required;
- The trussed legs are joined together by boundary conditions representing a rigid hull connected to the legs at the level of the holding system. Modifications to represent the leg interface with upper and lower guides and pinion systems, and the stiffness of the hull can be applied manually if required. This is not typically done for a vessel impact analysis, as additional hull flexibility is expected to increase compliance and hence reduce damage on the impacted leg. As noted under the future work section, tests could be performed to confirm this assumption;
- Leg scantlings are assigned Abaqus B31 beam-type element properties with through section integration points set to the Abaqus default. The cross-sectional properties of the tubular leg braces are specified using the Abaqus ‘Pipe’ definition and split-tubular chords are represented by the Abaqus ‘Arbitrary’ section definition. The ‘Arbitrary’ section property allows a split-tubular chord cross-section to be defined by a series of linked line segments, each with a separately defined thickness, as displayed in the cut-away view of a chord beam element taken from the Harvey Ward Abaqus model in Figure 2. Abaqus uses the ‘Pipe’ and ‘Arbitrary’ modules to auto-compute the relevant properties that are required for the B31 element, such as the overall cross-sectional area and stiffness about each axis;
- Chords and braces are assigned with a simple bi-linear elasto-plastic material stress-strain relationship. This type of material model is considered to be suitable for the type of analysis conducted in this study (Ref. [1]). Typically the linear elastic portion is defined up to the relevant material yield stress with a gradient defined by the Young’s modulus of steel, E = 210 GPa. This is typically followed by a plastic response with a linear work hardening up to a total plastic strain of 4.9%. A linear work-hardening gradient of E/100 is used as recommended in section 5.4.3 of Ref. [1]. Material properties can be adjusted to suit specific cases if necessary.

FORMATION OF PLASTIC HINGES

Whilst the elastic bending behaviour of a structural member can be adequately represented by a single beam-type finite element, several beam-type elements should be used for each structural member in an elastic-plastic model. As stated in Ref. [2], a sufficient number of nodes are needed to ensure an accurate formation of plastic hinges.

In the model of the Harvey Ward leg 6 elements were used to represent each chord and diagonal brace structural member in the leg and 4 elements used per horizontal brace as recommended in Ref. [2]. To ensure that the structural members are adequately represented by the selected mesh density, a mesh sensitivity study is usually performed by setting up a series of individual localised models of single structural members with properties assigned to match those used for the chords, diagonal braces or horizontal braces used in the global model. The structural members in the localised models are simply supported and subjected to a uniformly increasing lateral central point load. The bending moment at that node is recorded at the point when the component begins to deform disproportionately compared to an incremental increase in the point load. This bending moment is compared against the theoretical section plastic moment capacity to ensure the model aligns with theory. This check is not performed here since the purpose of the present analysis is to illustrate the methodology rather than to report on the specific structural capacities of the Harvey Ward jack-up unit.

AXIAL BUCKLING

As noted in the Basic Summary above, imperfections are introduced to the structural components to ensure they will buckle at appropriate load levels as recommended in DNV-RP-C208 (Ref. [1]). Similarly to the moment capacity test described above, a verification study is typically conducted using local models of structural components to ensure failure is induced at an expected axial load level. Typically it is found that introducing initial imperfection of 20-30mm results in axial capacities that match well against a relevant code strength check (e.g. ISO 19905-01 Ref. [8]), even when the structural members are represented by only two finite elements. This level of geometric imperfection is of course significantly greater than typical manufacturing out-of-straightness tolerances since, as described in Ref. [1], the induced imperfection equivalently captures other factors that reduce the axial buckling capacity of slender members compared to ideal conditions (e.g. residual stresses) and the simplifications of the relatively small number of beam elements used in the analysis. Also, this level of out-of-straightness has no significant effect on the axial, bending and shear distribution within the model under normal elastic loads.

In the Harvey Ward analysis reported here the selected out-of-straightness imperfections of 20mm were applied to the structural elements of the impacted leg by superimposing mode-shapes that were derived by performing an initial eigenvalue buckling analysis of the structure. Many of the mode-shapes obtained from the eigenvalue buckling analysis are localised, representing the buckling of individual structural members, so the superposition process used to set-up the imperfect geometry involves a large number of mode-shapes (of the order of ~100) to ensure imperfections have been introduced in all relevant structural members. Taking a brace member of the Harvey Ward jack-up as an example, an equivalent out-of-straightness imperfection of 20 mm gives a span/imperfection ratio of 250 which is in line with the ratios recommended in Table 5-7 of DNV RP-C-208 (Ref. [1]).

BOUNDARY CONDITIONS

For simplicity, for jack-ups like the Harvey Ward that are equipped with a rack and pinion holding system (it is understood the chocks were not engaged during the incident in the Tapti field), the legs are connected to the hull at the level of the lower guide. The effect of guide-gaps is not usually considered and the hull structure itself is assumed to be infinitely rigid in relation to the legs. In many cases these boundary conditions are expected to be conservative as they reduce compliance in the impacted leg. As noted under future work, systematic tests could be performed to quantify the effect of these assumptions in future assessments.

The rigid behaviour of the hull is represented in a straightforward manner in the Abaqus model by assigning a single 'rigid body constraint' to all nodes on the three legs at the lower guide and upper guide levels. Unless location specific conditions are being assessed, two separate boundary conditions are generally considered for the footings, one where the footings are pinned and the other with the footings are fully fixed. The example analysis reported in this paper uses fully fixed foundations. For location-specific cases, foundation fixity is considered and footing reactions are tested to ensure they fall within the soil yield envelope.

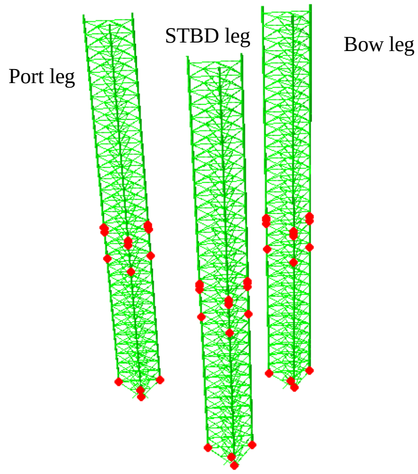


Figure 1 Harvey Ward Abaqus FE model auto-generated from JUSTAS model with nodes highlighted at hull level (at upper+lower guides) and footing level (at chord-to-spudcan and spudcan rotation points)

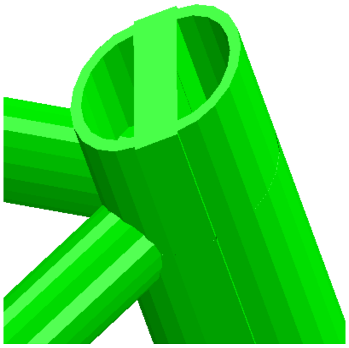


Figure 2 Cut-away view of beam element representing a chord of the Harvey Ward

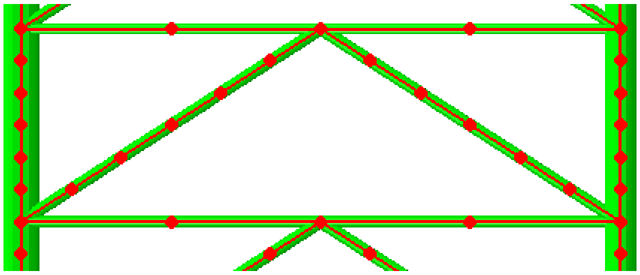


Figure 3 Elevation of single bay showing beam element mesh

DAMPING

Damping is introduced into the model using Rayleigh damping as is typical for non-linear dynamic analyses. For this type of damping, the equivalent critical damping coefficient is not constant across all natural periods of the structure. Hence the mass-proportional damping coefficient and stiffness-proportional damping coefficient in the Rayleigh damping model are selected such that they give an equivalent critical-damping value that may be considered to be reasonable for salient natural periods of the structure. One set of salient points are the natural periods of the individual legs of the jack-up and for that an equivalent critical-damping of < 2% is targeted. Other salient points are the global surge, sway and yaw periods of the jack-up and for these critical damping coefficients < 7% are targeted.

LOADING

Once imperfections have been applied to the geometry of the impacted leg and the boundary conditions have been defined, a gravity load case is executed to settle the structure elastically under its own self-weight. The hull weight is typically represented by appropriate point masses assigned to the nodes that form part of the rigid-body definition that represents the hull. The leg weight is auto-calculated by the model based on the density assigned to each portion of the leg. Typically a standard steel density of ~7,850 kg/m^3 is applied, but this can be increased to represent additional structures (raw water pipes etc.) or added mass for submerged sections if these are considered important for the dynamic response. Raw water structures and guide rails can also be modelled explicitly in which case care should be taken to ensure they do not contribute inappropriate stiffness and attract load away from leg structure that is being assessed.

After the static gravity load has been applied a point mass, in this example of 7,000 tonnes, representing the impacting vessel, including added mass, is set at a velocity of 2 m/s to initiate the impact event. This gives the ship an initial kinetic energy (and hence ship impact energy) of 14 MJ typically recommended for a broadside impact as discussed in the introduction. It is noted in several recent analysis projects requests to consider significantly higher impact energies of the order of 30-50 MJ have been received, mainly as a result of the increasing displacement of attending vessels. The impact is applied to only one of the leg chords at a time, with load application points at mid-bay and brace node levels and under several loading directions considered (whilst accounting for symmetry to avoid excessive replication of analysis cases). Note that in the actual Harvey Ward impact case the vessel may have been more massive; for instance one estimate reported in Ref. [9] suggests the available energy at impact could have been about 22.5 MJ. The actual impact energy involved is unknown and the purpose of this assessment is to demonstrate a vessel impact analysis conducted to standard impact criteria so 14MJ is used here.

With reference to Figure 4 the 1996 impact on the Harvey Ward occurred on the starboard leg such that the majority of loading was resisted by a single face of the trussed leg (face ‘A’ to ‘B’ in Figure 4). The Harvey Ward analysis model used here was set up with geometric imperfections induced in the starboard leg structure. An impact location and direction were selected that are believed to be representative of the conditions of the actual impact event, although the details on these factors are not clearly recorded. The impact load was applied to the aft starboard chord of the starboard leg with the loading direction selected to approach from bow (labelled as 0 degrees in Figure 4).

To transfer load to the impacted chord a non-linear ‘ship spring’ was connected between the ship mass node and the node on the leg chord that was impacted as shown in Figure 5. Note that some bowing of the braces is visible in the plan view of the leg in Figure 5, which is due to the induced imperfections discussed in the previous section. The ‘ship spring’ represents the force-indentation curve and hence impact energy absorption of a ship’s structure during the impact. The force-indentation curves that are recommended by DNV in various publications, such as Ref. [7], and replicated in Figure 6, have been used here. This curve represents a rather specific case, of a notional boat of 5,000 tonnes displacement impacting against a 1.5 m diameter column, but it is commonly applied in jack-up vessel impact analyses and is sufficient to illustrate the methodology described in this paper.

It has been noted above in some recent analyses requests we have been asked to consider impact energies that are significantly higher than the standard case, representing higher vessel displacements and/or impact velocities. The presented force-indentation curve in Figure 6 could potentially underestimate the impact force and impulse for a ship of a different structural configuration. In such cases an alternative force indentation curve, such as that from Norsok N-004 Section A.3.5.1 (Ref. [10]) for a ~125,000 tonne tanker bulb bow-on impact has been applied, in the absence of a wider selection of published curves. There is however a need for a greater variety of ‘ship-springs’ to represent a range of vessel types, impact velocities, and to account for the diameter of impacted elements.

SOLVER

Non-linear dynamic analysis problems can be solved in Abaqus using either an implicit time-integration routine (Abaqus Standard) or an explicit time-integration routine (Abaqus Explicit). Each solver-type is appropriate for the analysis of a different set of phenomena, which can be categorised in terms of the overall duration of the phenomenon and the level of non-linearity in the system. The explicit solver is generally suited to very short duration events (e.g. ballistics, blast and hyper-velocity impact scenarios) and those involving excessively large deformations. A ship-impact would be expected to last somewhere between 1 and 10 seconds, and whilst the crushing of the ship structure would be a highly non-linear event, this response is represented by a simplified non-linear spring and the dynamic response of the jack-up structure that is of interest here would, relatively, be less non-linear. On this basis the Abaqus Standard implicit solver is selected for this assessment.

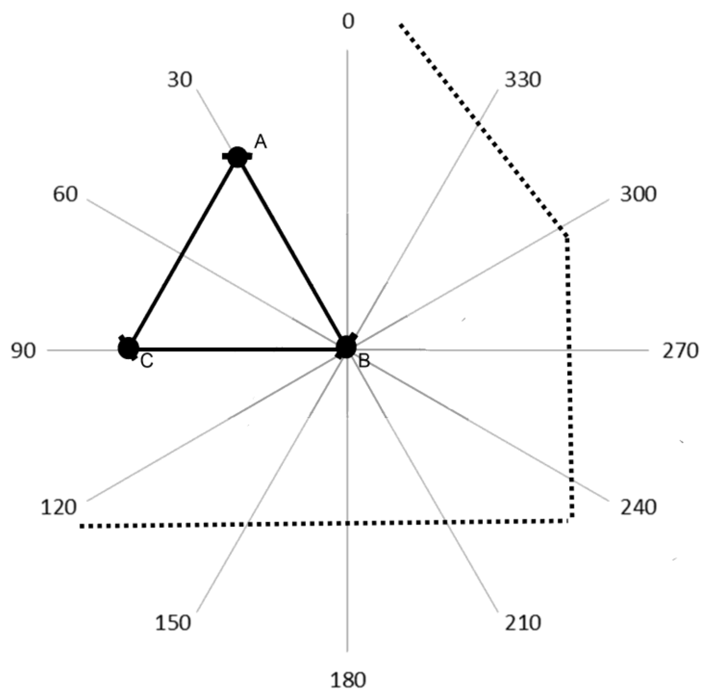


Figure 4 Example of loading directions key plan for a Starboard leg

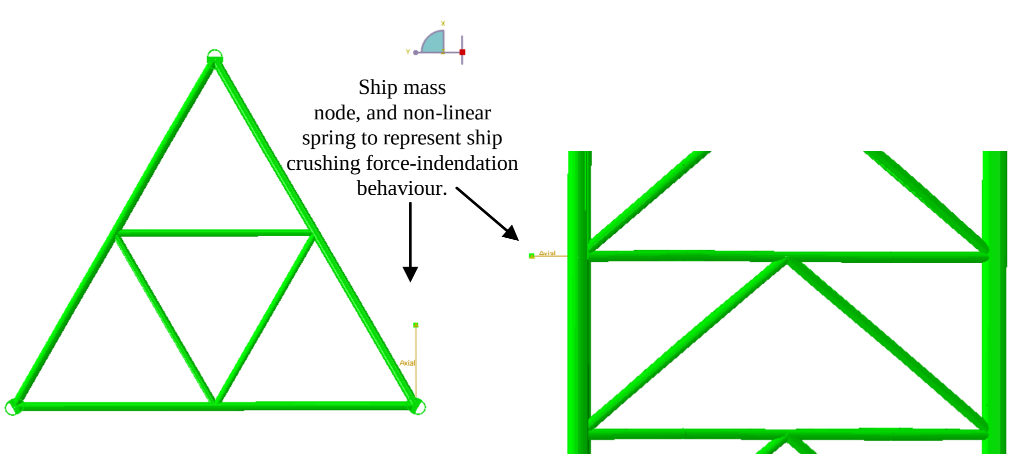


Figure 5 View of loading point in plan and side views

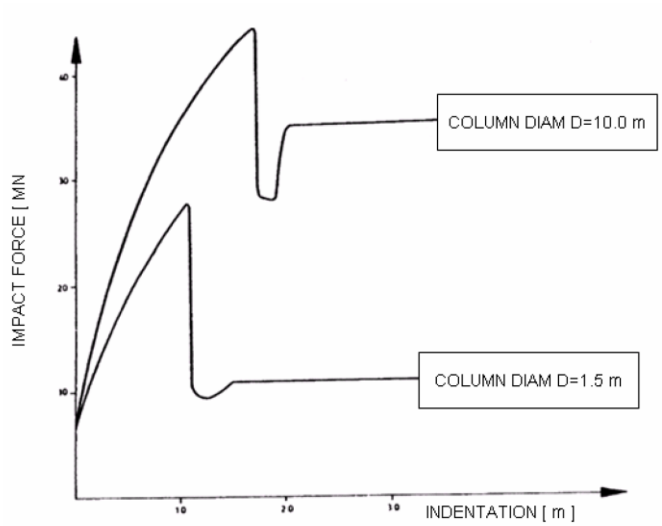


Figure 6 Force-indention curve recommended in DNV-RP-C104 for a broad side impact of a 5000 MT boat against an infinitely stiff column (Figure 8-3 from Ref. [7])

ACCEPTABILITY CHECK AND FAILURE CRITERIA

The structural safety critical elements (SCE's) for a jack-up are considered to be the leg structural system (chords/braces) and the holding system, and hence both items are usually checked for acceptability. It is generally assumed in the ND analysis that any joint failure would only be observed after a significant failure of the main structural members such as significant distortion of braces; this sequence of failure is often the design intent in jack-up leg structural designs. ND would not usually perform joint strength checks unless there is a particular concern about a jack-up legs joint details that suggest the joints could fail before a primary structural element would (e.g. if the relative dimensions of braces element vs. chords suggest susceptibility to a punching shear failure mechanism). It is noted in Ref. [6] that for the Harvey Ward incident some welds had failed, but these failures corresponded to connections of significantly buckled braces.

Due to redundancy, the overall leg structure would be expected to maintain a stable equilibrium if a limited number of structural members fail. If the jack-up leg structure is overloaded then a significant number of members would fail and redundancy would be lost. The leg structural model is capable of forming collapse mechanisms under such situations.

For the leg structural system, the model is usually checked for equilibrium for two phases during the analysis, firstly from the application of the ship impact load until the impacted rig comes to a stable equilibrium condition and also after the subsequent application of a 1-year environmental event. If a stable equilibrium is found to be present after both of these steps then this is considered sufficient to conclude that overall leg chord and brace structural integrity would be maintained during and after a reasonable vessel impact event. Further checks are then performed by comparing reactions at the holding system and footings against allowable limits. It is noted an environmental loading step has not been included for the example analysis preformed in this paper.

DAMAGE OBSERVED DURING THE ORIGINAL INCIDENT

The ultimate test for a structural response analysis methodology is to compare the results of the analysis against an actual observed event. Few events of this sort are detailed in the public domain, which is one reason why the Harvey Ward vessel impact incident in the Tapti Field (offshore Mumbai) reported in Ref. [6] is useful. Indeed, the same event was used to test a vessel impact analysis in Ref. [9], where is it noted there are no other jack-up vessel impact cases documented in sufficient detail to use as a comparative case. Nevertheless many variables were difficult to define precisely from the Harvey Ward vessel impact event and assumptions have to be made in any analysis.

The event was also particularly of interest for testing the current methodology for two further reasons:

- It was noted in Ref. [6] that attempts "*to predict the observed deformation through elastic and plastic large deflection analysis provided results that were inconclusive and did not yield the confidence required to continue such a pursuit*". Ref. [5] further notes the difficulty in performing such analysis during the late 1990's when the event took place, and discusses numerous simpler analysis methods. Approximately eight years after the event, Ref. [9] successfully replicated the Harvey Ward damage profile using non-linear FE analysis as part of a detailed university research project. Despite this, past attempts within ND to adopt non-linear FE analysis as the primary tool for jack-up vessel impact showed the method to be cumbersome for routine engineering consultancy work. The analysis reported herein is efficient to set-up and execute, providing an opportunity to reflect on the progress that has been made over the years to now make this type of computation straightforward.
- Other vessel impact analyses performed using the present nonlinear dynamic FE analysis method have yielded damage profiles that are relatively different to what was observed for the Harvey Ward event. In particular the Harvey Ward event demonstrates a remarkable symmetry in the observed damage characteristics as discussed below, and that is not often present for other leg designs and impact scenarios that have been analysed using the present method. By testing the Harvey Ward model here, it is possible to infer whether the cause of this is due to differences in rig design or a limitation in the analysis implementation.

With reference to Figure 7 the damage profile as reported in Ref. [6] for the Harvey Ward vessel impact consisted of the following features on the impacted leg:

1. Diagonals between chords A and B, adjacent to chord A, from lower guide to waterline bent and buckled;
2. Diagonals between chords A and B, adjacent to chord B, from waterline downward bent and buckled over a range of 4 bays;
3. Chord A and B bowed out of line by ~4ft at the waterline;

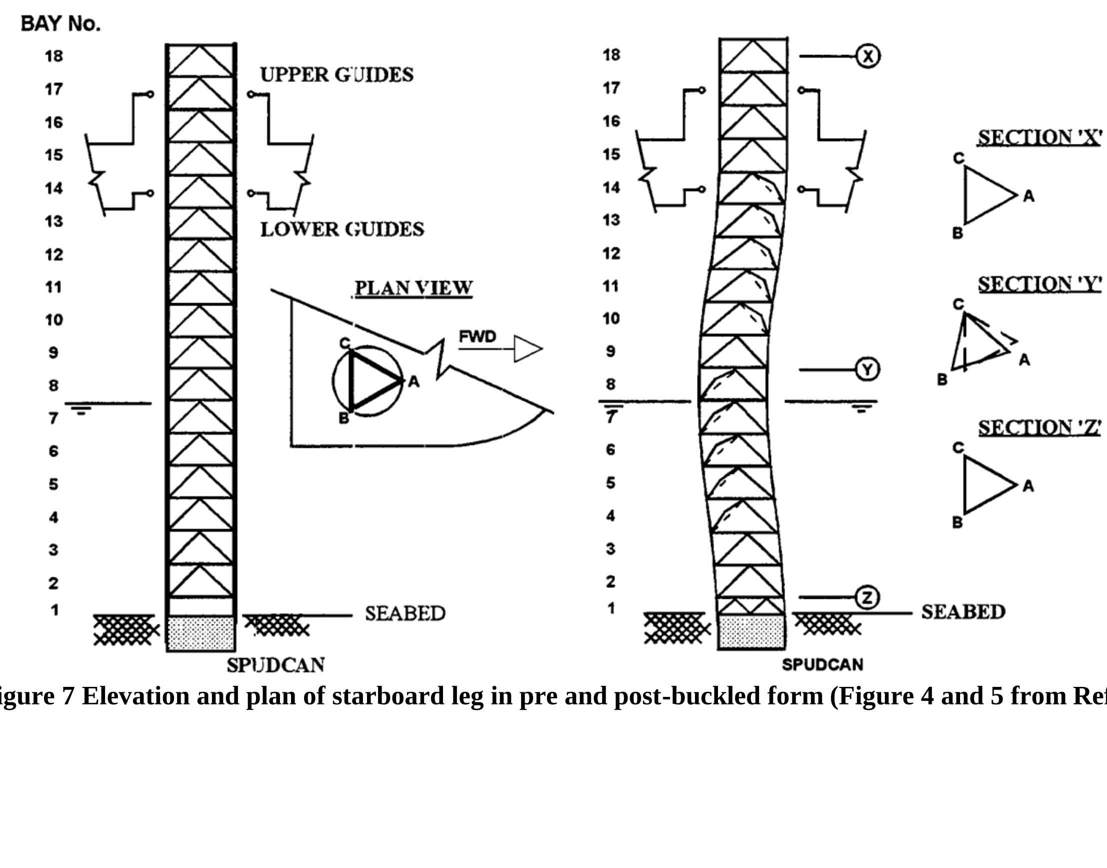


Figure 7 Elevation and plan of starboard leg in pre and post-buckled form (Figure 4 and 5 from Ref. [6])

4. Horizontal braces above the waterline bent downwards at connection point with buckled diagonal braces;
5. Localised bending of braces at the waterline and just below waterline believed to be in the region where contact was made with the barge;

The non-impacted legs showed no signs of physical damage. Further details of damage observed are provided in Ref. [6].

ANALYSIS RESULTS

The Abaqus analysis of the Harvey Ward will differ from the original event to some extent due to the assumptions made in the model which do not match the original conditions. The intention here is however to capture the broad response of the jack-up to impact, and not to replicate the exact dimensions of the damage because the precise conditions of the impact are so difficult to establish.

To recap, such assumptions include: load application via a standard 'design' vessel mass and impact velocity applied through a code-defined nonlinear ship-spring, impact applied to the aft-starboard chord of the starboard leg of the model at an assumed impact direction, structural geometry initiated with code-defined equivalent imperfections and full fixity assumed at the seabed.

The analysis was run for a 100 second time period, after which the jack-up was observed to have mostly settled into its equilibrium state other than for some small movements and vibrations. Images of the resulting damage profile at the end of the simulation period are shown in Figure 8. Comparison against Figure 7 demonstrates that the analysis aligns well and has correctly replicated the following features of observed damage:

1. Diagonals between chords A and B, adjacent to chord A, from lower guide to waterline bent and buckled;
2. Diagonals between chords A and B, adjacent to chord B, from waterline downward bent and buckled;
3. Chord A and B bowed out of line in an identical manner. The maximum distortion of the chords is ~5.7ft, compared to 4ft observed at the Tapti field. One possible reason for this could be because the equivalent imperfections that are introduced and required to meet an accepted level of structural reliability results in a structure that would, overall, be expected to be weaker than the actual structure was during the Tapti incident. A test performed using a model with no initial imperfections demonstrated that brace buckling is still induced due to imperfections that are induced in the braces during the impact, by rotation of the chords, but this buckling occurs at higher axial load levels resulting in a reduced maximum distortion of the chords.
4. Horizontal braces above the waterline bent downwards at connection point with buckled diagonal braces;
5. No damage observed on the non-impacted legs.

Localised bending in the impact region is not replicated because the ship impact is applied at a single point.

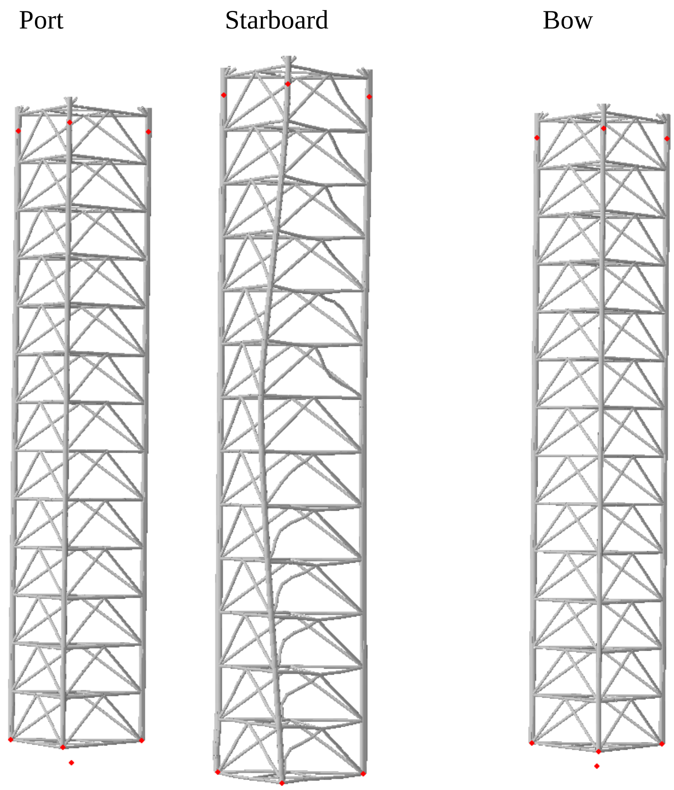
Salient parameters from the analysis are provided in Table 1. Interestingly, most of the impact energy has been permanently imparted to the jack-up, and of that much of it has been absorbed in the form of permanent plastic straining of the braces of the impacted leg. In other 14 MJ impact assessments performed by ND for different jack-up leg designs, it has been more typical to find only 50-60% of the impact energy to be absorbed by the jack-up, much of it elastically with the remaining 40-50% seen in the rebound kinetic energy of the point mass that represents the impacting vessel.

As stated in Table 1, the jack-up hull centroid settles by 0.1 m due to vertical shortening of the impacted leg as it deforms; this releases 2.22 MJ of potential energy and this needs to absorbed within the jack-up structural system in addition to the energy imparted from the impacting vessel. At the point when the analysis was terminated (100 seconds post-impact) the structure was observed to have settled into its final state for at least one minute, but there were still small oscillations of the hull around its final position and vibrations within the leg structure. The kinetic energy of these small movements, at the 100 second snapshot, actually amounts to 2.12 MJ of kinetic energy, almost negating all of the potential energy released due to hull settlement. After 100 seconds some energy will have already dissipated through damping, and the rest of this kinetic energy would also eventually dissipate in the same way if the simulation were run for a long enough time-period.

CONCLUSION

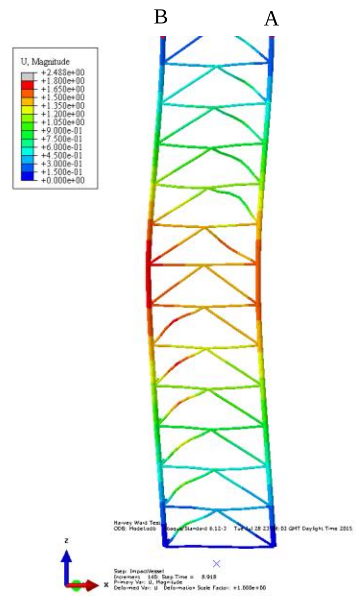
The similarity in the general damage characteristics between the Harvey Ward vessel impact incident and the analysis model described in this paper has demonstrated that the applied methodology is suitable for adequately assessing the vessel impact capability of this type of jack-up rig. The modelling can be undertaken quickly by using a Python script to transform an existing JUSTAS model into a model that can be analysed using a large deflection, elasto-plastic, non-linear dynamic FEA model using Abaqus. The Abaqus analysis permits an examination of the ability of the jack-up to survive the selected impact event.

View of post-impact geometry of the legs in the region below the lower guide down to footings:



Deflection scale x 1
Perspective level with waterline

Close-up of bays in face A-B with buckled braces above and below waterline:



colourmap: deflection (m)

Plan view of deflection at impacted bay overlayed on original orientation:

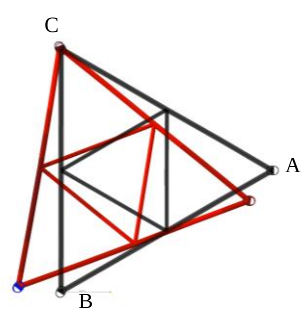


Figure 8 non-linear FE analysis results

Table 1 Salient parameters from analysis

Overall impact energy (MJ)	14.0
Impact energy permanently imparted onto jack-up structure (MJ)	12.9
Plastic strain energy absorbed by leg structure (MJ)	10.9
Maximum impact force (MN)	9.9
Ship impact duration (s)	4.9
Final hull inclination post-impact (deg)	0.2
Final vertical settlement of hull post-impact (mm)	36.0
Maximum hull sway at hull centroid during impact (m)	0.10
Maximum deflection of the contact point on the leg (m)	1.75

FUTURE WORK

Having confirmed in the study described above that the analysis method described is able to replicate the failure profile of the Harvey Ward leg structure, the method can be used with increased confidence to undertake future studies. In addition to specific ship-impact analysis cases for jack-ups, the techniques described here would also be suitable for undertaking some more general investigations into the response of jack-up platforms to ship impact damage. Such studies might include investigation of the response characteristics of different jack-up leg bracing designs. In particular it is expected that the bracing scheme, relative slenderness and strength of bracing elements, and leg shear stiffness vs. bending stiffness could all influence a jack-up's response to vessel impact significantly. The method can be used to investigate the influence of certain simplifications that are currently applied in vessel impact analysis, with particular attention to the following omissions: lower and upper guide gaps, guide and holding system stiffness and hull related stiffness.

Finally two specific cases are worthy of additional study. The nature and extent of the ship crushing damage experienced during impact can be expected to have an influence on the behaviour of a jack-up rig response and the most appropriate model of ship crushing needs to be selected. Also further investigation of appropriate non-linear elasto-plastic models to represent the behaviour of the spudcan soils will be valuable for site specific cases where the fully fixed or pinned conditions are not appropriate. On this point, initial assessments have been performed using the Abaqus 'spudcan' element, noting that it currently has the following limitations for this type of analysis: the element is currently 2D, it does not include stiffness degradation in the elastic range and the yield interaction equation cannot be defined to match the ISO equation for clays (Ref. [8]).

REFERENCES

[1] DNV Recommended Practice, Determination of Structural Capacity by Non-linear FE Analysis Methods, June 2013, DNV-RP-C208.

[2] DNV, SINTEF and BOMEL, Ultiguide – Best Practice Guidelines for Use of Non-linear Analysis Methods in Documentation of Ultimate Limit States for Jacket Type Offshore Structures, April 1999.

[3] Health and Safety Executive, Hazardous Installations Directorate Offshore Division - "Technical Policy Relating to Structural Response to Ship Impact", Rev. A, Dec 2006.

[4] DNV Recommended Practice, Design Against Accidental Loads, Oct 2010, DNV-RP-C204.

[5] P. Gjerde and S. J. Parsons, Assessment of Jack-up Boat Impact Analysis Methodology, in proceedings of The Jack-up Platform Conference 1997 at City University, London (1997).

[6] R. Allen, P. R. Geiger and R. W. P. Stonor, Recovery Of The Jack-Up "Harvey H. Ward" Following Impact Damage To A Leg", in proceedings of The Jack-up Platform Conference 1997 at City University, London (1997).

[7] DNV Recommended Practice, Self-elevating Units, January 2012, DNV-RP-C104.

[8] Petroleum and natural gas industries – Site-specific assessment of mobile offshore units, Part 1: Jack-ups, September 2012, ISO 19905-1:2012.

[9] T. Lerchenmüller, Vessel Impact Analysis for Jack-Ups, MSc Thesis Delft University, September 2004.

[10] NORSOK Standard N-004 (October 2004), "Design of Steel Structures", Rev.2