FINITE ELEMENT ANALYSIS OF SPREADER BAR BY UTILIZING THE ARRANGEMENT AND CONNECTION OF PADEYES

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ABSTRACT

Heavy lifting is one of several methods used for marine installation of heavy equipment while spreader bar (SB) is widely used in heavy lifting. The application of SB is mainly to avoid an overstress in the structure when being lifts which due to sling arrangement in bridle. SB is typically made of high strength tubular pipe with padeye/trunnion attached. Comparison between 3 types of padeye arrangements on SB is made based on its strength properties as reflected in API RP 2A 22nd edition to ensure its optimum design centred on material's weight and welding work criteria. The buckling load for lightest pipe among 3 types of SB is then calculated. Finite element analysis (FEA) is performed to verify design stresses and buckling load of selected pipe. From observation, the thickness of tubular pipe can be reduced up to 50 percent compared to other SB types by setting the centre line (CL) of upper padeye to be in line with tubular pipe axis.

KEYWORDS: *Spreader bar, heavy lifting, Euler stress, padeye, finite element*

1.0 INTRODUCTION

Nowadays, major drilling and production facilities of oil and gas industry are located offshore and thus installing this equipment necessitate efficiency and safety. The industry has developed a number of ways to overcome heavy lift challenges through experience and innovation. Heavy lifting is among main methods of marine installation for heavy equipment. The conventional way to install major facilities, such as topsides and production equipment, is through heavylift vessel (www.rigzone.com). Heerema's Thialf and Saipem's S7000, (by then renamed) were upgraded such that the combined lifting capacity of two cranes on each vessel is 14200 tonnes and 14000 tonnes respectively. The Balder and Hermod semi-submersible crane vessels (SSCV) were each fitted with two enormous cranes. S7000 is well-known for holding world record for an actual lift of 12150 tonnes and for lifted 9500 tonnes jacket in 2007 for Pemex in dynamic positioning mode. Also, Thialf has a staggering lifting capacity of 14200 tonne

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or equivalent to weight of more than 1180 fully laden London buses (offshore-technology.com).

During heavy lifting, the structure is subjected to higher stress due to its self-weight and dynamic load from variation of hoisting speeds, crane, vessel motions, cargo barge movements, object movements and others. (DNV VMO, 2014). Thicker and higher strength of steels are used in designing installation aids for heavy lifting. The use of slings in bridle arrangement configuration will induce stress in the structure. This additional stress can be eliminated using SB. By utilizing SB to vertically line up the sling on top of structure's lifting point, this will allow a straight pull movement. SB is a structure designed to resist compression forces induced by angled slings, by altering line of action's force on lift point into the vertical plane. (GL Nobel Denton, 2013).

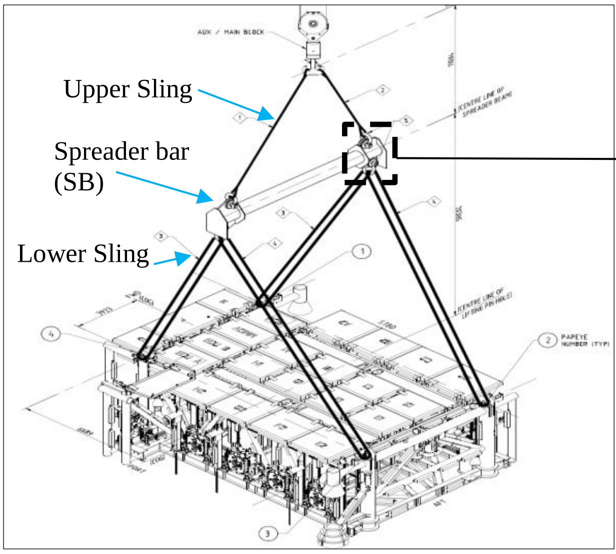


Figure 1. Typical rigging arrangement using single SB

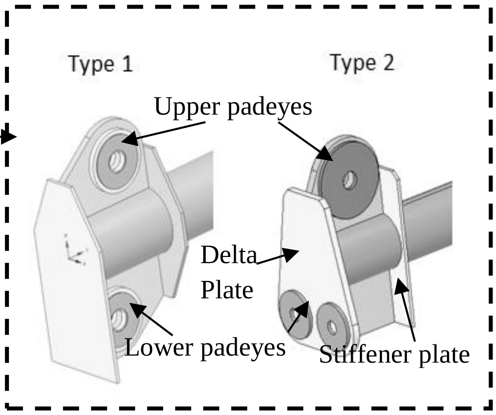


Figure 1. Common SB padeye design

Tubular pipe is commonly used in designing SB, as shown in Figure 1, due to its constant properties in any sectional direction if compared to I beam which have a combination of strong and weak axis. There are two types of SB padeye design usually found in offshore lifting (Figure 2) where the differences are on bottom padeye's design. Where, bottom part of type 2 padeye is fabricated in form of delta plate whereas bottom of type 1 padeye is sharing same plate with its top.

Type 1 is using less material and welding filler because of simplicity of lifting point (padeye) connection design. Though by sharing a same plate, bottom shackle's need to be de-rated (depend on manufacture) since side loading applied to the shackle will caused larger size of shackle (Figure 3). Increased size of shackle will lead to larger plate needed and stimulate weight gain of lifting system, whereas type 2 will require more material to be used in fabricating delta plate. By introducing delta plate, top padeye will need to be shifted away from bottom padeye to avoid clashes between top shackle and delta plate. This arrangement will result in a bigger in-plane moment hence thicker pipe need to be used.

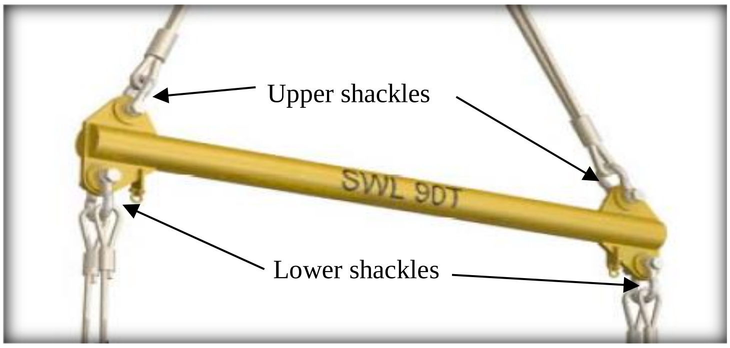


Figure 3. Position of shackle at spreader beam (Product Datasheet, http://www.nli.no)

The plate used to fabricate padeye is made from through-thickness (Wang, et al., 2015) property material to avoid failure due to lamellar tearing during lifting. Lamellar tearing is a separation in parent or based metal caused by through-thickness strains. Such strains are induced primarily by weld metal shrinkage under conditions of high strain. When detected, lamellar tearing can result in often difficult and costly repairs and subsequent construction delays (Ship Structure Committee, 1979). Furthermore, required type of steel is barely available in the market therefore require to be procure within at least 3 months in advance, depending on its availability. Therefore, if any defect detected during fabrication, schedule of offshore installation campaign will be drag forward until procurement of material is completed.

Also, the limitation on rigging weight due to operational/material handling issue or as per client's requirement on "Not to Exceed Weight" need to be considered. Hence, designing SB using relatively thinner material for weight reduction and lessen welding work to reduce risk of defect in welding is essential.

In this study, an advanced SB padeye design (Type 3) and comparison analysis with other two common SB padeye design is introduce where main plate of padeye (Figure 4) is slotted through tubular pipe in order to get maximum lifting capacity by transferring load through weld at joint. Tubular joint without stiffener inside the chord will cause chord to experience punching stress thus reducing its capacity. Therefore, slot in connection is ideal for designing connection between lifting point and tubular pipe. Lifting point on SB is installed right above lifting point of module to ensure that vertical pull conditions can be achieve without overstress due to sling arrangement occurred in lifted structure.

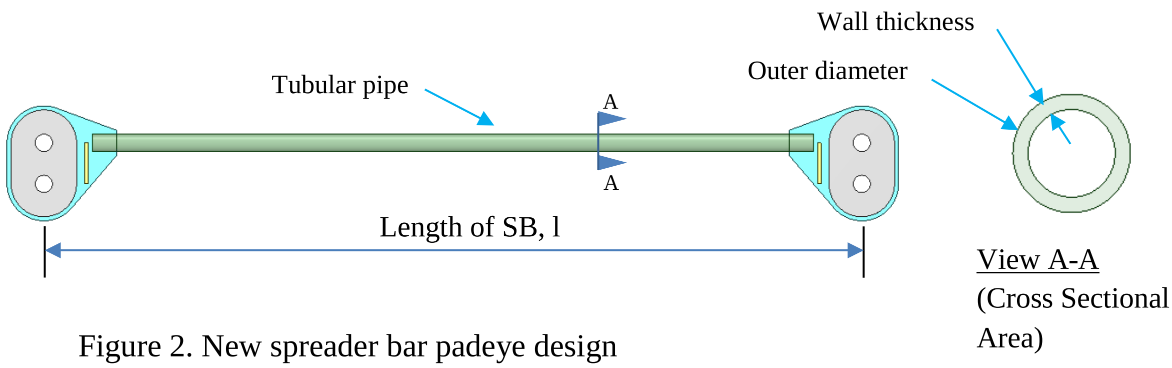


Figure 2. New spreader bar padeye design

2.0 MATERIAL AND METHODOLOGY

2.1 Material

For the purpose of this study, SBs are design to lift the 19620N structure. Lifting arrangement is shown in Figure 1. The length of SB is fixed to 800mm based on distance between two lifting point of structure and dimensions of SB's geometry is detailed in Table 1 below.

Table 1. Geometry details for each SB

Items	Type 1	Type 2	Type 3
Outer Diameter (mm)	42.40	48.30	26.9
Wall Thickness (mm)	2.60	4.90	2.0
Cross Sectional Area(mm^2)	325.10	668.10	156.45
Slenderness Ratio Kl/r	56.73	51.81	120.77
Total Weight (N)	54.76	70.49	26.33

Material properties selected for fabrication of plates and tubular are mild steel which in compliance to ASTM A36 for plate and ASTM A106 Grade B for pipe. Calculations are based on minimum yield strength of relevant material grade as specified in Table 3.

Table 2. Material properties

Density in air	7.74E-5 N/mm^3
Young's Modulus, E	210000 MPa
Shear Modulus, G	80000 MPa
Poisson's ratio	0.3

Table 3. Strength of Material

Steel Grade	Yield Stress (MPa)	Tensile Strength (MPa)	Remark
ASTM A36	248	400-550	For Lifting Point (padeye)
ASTM A106 Grade B	240	415 Min.	Spreader

2.2 Tubular Design Criteria Mathematical Modelling

Force in horizontal component produce a compressive stress on tubular and assume to be matched with Euler's theory of buckling. Euler formula is derived for an ideal or perfect column which the theory is simple enough to be applied. Though, the formula is constructs on a couple of assumptions that rarely comply with real conditions as highlighted below (McKenzie, 2006):

- The compression load acts through absolute centre of columns cross sectional area.
- The column is completely a long, slender, straight and homogeneous even before concentric axial compressive load is applied. Slenderness is defined as the ratio between height and cross-sectional dimensions of column. Slender columns which subject to buckling will produces additional moment resulting in significant reduction of column capacity.
- The column's material is elastic and follows Hooke's law.
- There are no imperfections in the column.
- Lateral deflections of the column are small compared to overall length (the column's displacement is small).
- The column is pin-jointed at each end and restrained against lateral loading.
- There are no residual stresses in the column.
- There is no strain hardening on the material.

Since self-weight of SB is relatively too small compared to sling load, it is possible to neglect the weight from here. Common design of SB normally produced moment due to padeye eccentricity as shown in Figure 5.

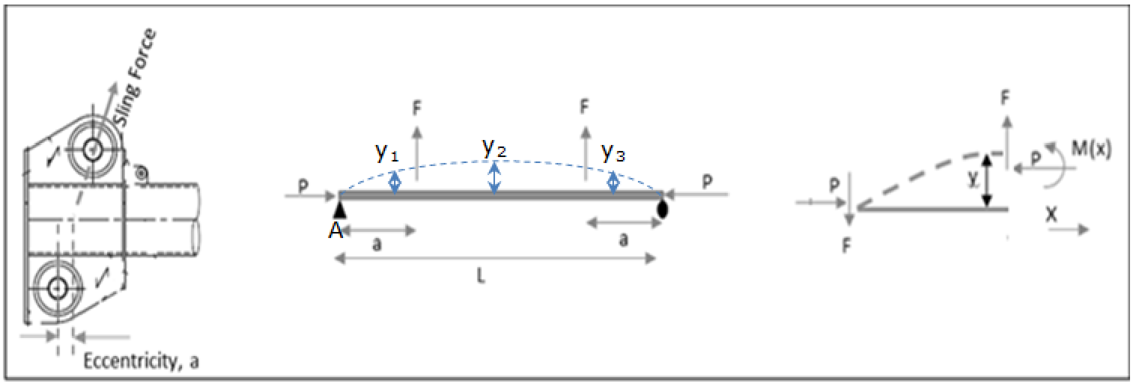


Figure 3. Free Body Diagram for SB type 1 and 2

Total moment at a point x from either end (boundary condition) gives:

$$M(x) - Py - Fx = 0 \qquad 0 \leq x \leq a \qquad (1)$$

$$M(x) - Py - Fa = 0 \qquad a \leq x \leq (L - a) \qquad (2)$$

$$M(x) - Py - FL + Fx = 0 \qquad (L - a) \leq x \leq L \qquad (3)$$

Where:

M = Total Moment, *P* = Axial Load, *F* = Vertical Load

P and F are derived from calculated sling load based on rigging arrangement as shown in Figure 1.

From equation (1), (2) and (3), it shows that SB is needed to resist axial compressive force and bending moment. Thus, Figure 5 shows the eccentricity on geometry that generates moment in SB where the bending moment created will reduced the capacity of SB.

Any force that applied to SB at neutral axis resulted in a purely compression force in tubular pipe. Therefore, forces that are not lined up with neutral axis generate bending force or bending moment. SB that is subjected to bending forces and/or bending moments is more difficult to be properly design and will no longer be simple and light weight construction as preferred (heavyliftnews.com).

To eliminate eccentricity, padeye's top is moved to CL of tubular pipe and left Euler buckling as an only mode of failure for SB. This concept is illustrated in Figure 6.

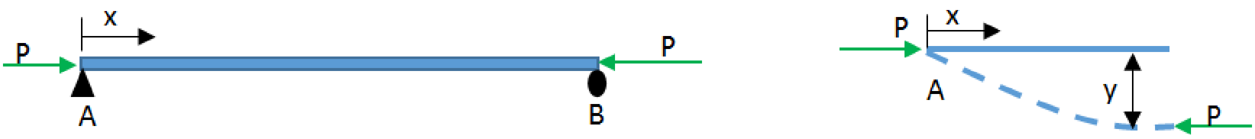


Figure 4. Free Body Diagram for New SB Design

When lateral displacement is y, summation of moments on beam section is (Chen et al., 1999):

$$M + Py = 0, \; where \; M = EI\frac{d^2y}{dx^2}\;, thus \; EI\frac{d^2y}{dx^2} + Py = 0 \qquad (4)$$

Solution for equation for is $y = Bsin\,(kx)$ (5)

By solving equation (4), smallest value of P is known as critical load, buckling load, or Euler formula:

$$P_E = P_{cr} = \frac{\pi^2 EI}{L^2} = \frac{\pi^2 E}{\left(\frac{kL}{r}\right)^2} \qquad (6)$$

According to API RP2A WSD 22nd Edition, allowable Axial Compressive stress, F_a must be determined from the following AISC formulas for members with D/t ratio or less than 60. In the (AISC ASD, 9th Edition) equations for allowable compressive stresses, various imperfections such as effect of residual stresses, actual end restraint conditions, crookedness, and small unavoidable eccentricities are empirically taken into account.

The API code which is based on AISC 9th Edition requirement assumes arbitrarily that the elastic buckling holds valid when stress in the column is not greater than one-half of the yield stress (Fy/2) (J.S.Arora, http://user.engineering.uiowa.edu).

For column having effective length less than Cc, it is assuming the failure by crushing of the material induced by predominantly axial compressive stresses. Failure occurs when stress over cross-section reaches yield or crushing value for the material.

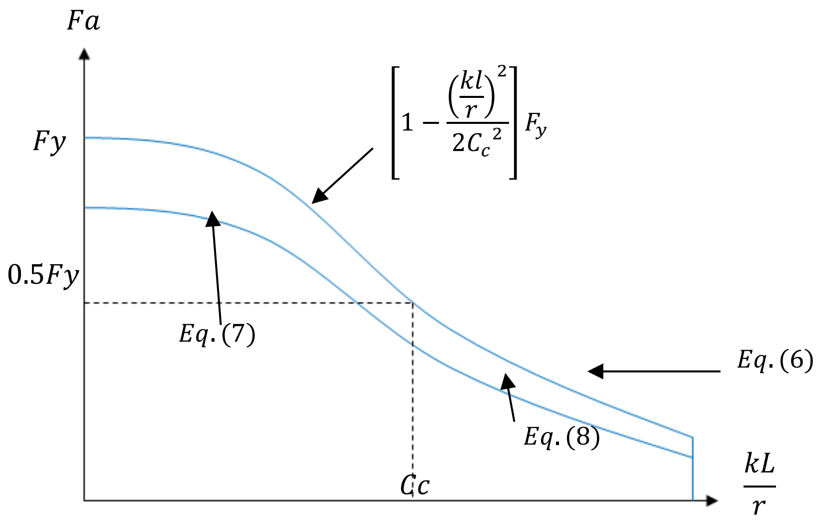
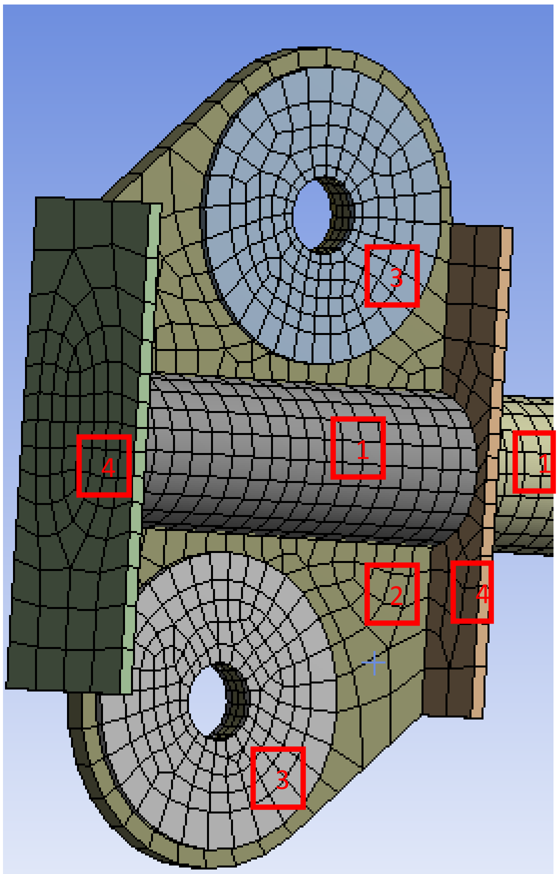


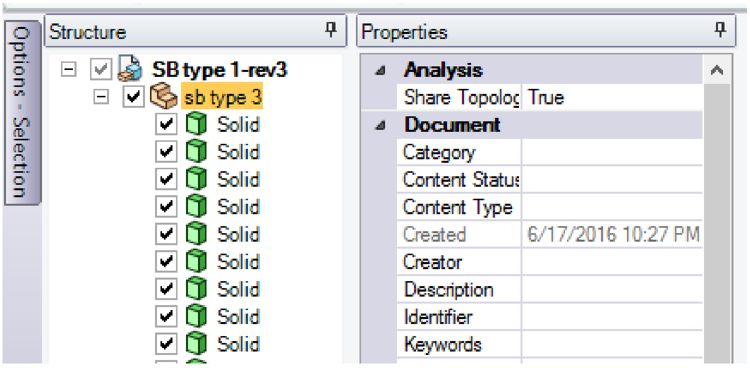
Figure 5: Variation of critical stress and allowable stress as specified by the API code

3.0 FINITE ELEMENT ANALYSIS

Finite Element Analysis is widely used in offshore industry to design offshore and subsea structure. All structures were modelled using Space Claim (ANSYS Package).

In SpaceClaim, spreader bar components i.e tubular pipe, main plate of padeye, cheek plate and stiffener are group together and Shared Topology is activated. Shared Topology occurs is triggered when bodies are grouped into multibody parts. It allows for a continuous mesh across common regions where bodies touch, instead of having to define Contact Regions in the ANSYS Workbench. These bodies share topology in the region where they are in contact with, so the mesh is continuous across part as shown in Figure 8. It is often, but not always, more desirable for analysis to have a continuous mesh across parts than to use contact (ANSYS 14.5 User Guide).





Legend:
1-Tubular Pipe
2- Padeye-main plate
3. Padeye-cheek plate
4. Stiffener plate

Figure 6. Typical details of SB components and continuous meshing across the parts

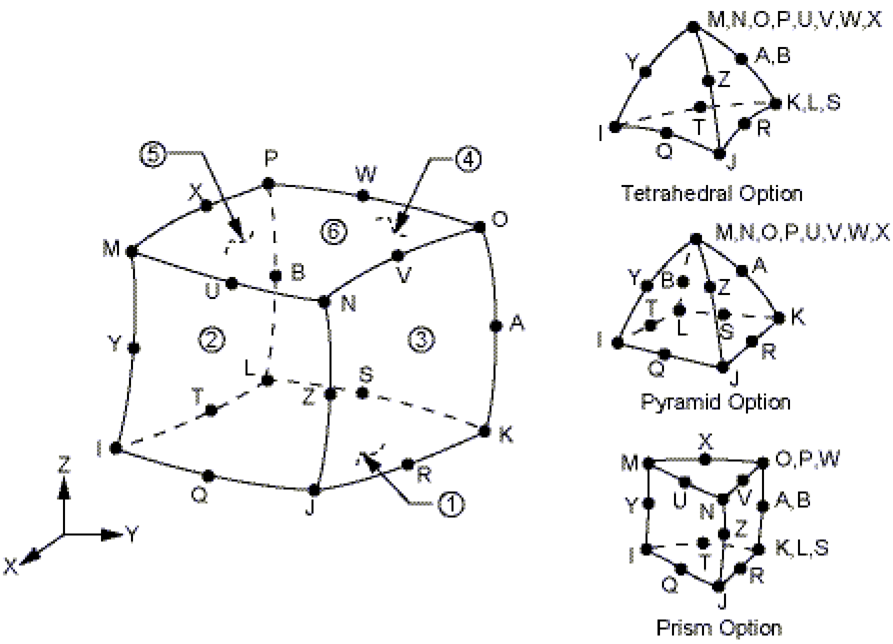


Figure 7. SOLID186 homogeneous structural solid geometry

The model then exported to ANSYS for assignment of materials and contact details. The meshing is performed with element size of 5mm as shown in Figure 9 and SOLID186 Element is assigned to the geometry. SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behaviour where the element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The geometry, node locations, and element coordinate system for this element are shown in Figure 9. A prism-shaped element may be formed by defining the same node numbers for nodes K, L, and S; nodes A and B; and nodes O, P, and W. A tetrahedral-shaped element and a pyramid-shaped element may also be formed (ANSYS 14.5 User Guide) as shown in Figure 9.

Summary of mesh statistic for each type of SB is as shown in Table 4. The static structural analysis is performed to determine the stress level for imposed load. Then the data is exported to linear buckling module to find critical buckling load for each type of SB.

Table 4. Mesh Statistic for each type of tubular pipe

Item	**Type 1**	**Type 2**	**Type 3**
Nodes	12251	124060	74675
Elements	8766	25018	28507
Mesh Metric (Average Aspect Ratio)	4.78	4.19	2.83

Bearing load is then assigned to the surface of upper padeye's pinhole representing dynamic sling load (DSL) applied to SB as shown in Figure 10, 11 and 12 for SB type 1, 2, and 3 respectively. As defined by ANSYS, the bearing load simulates radial forces only and applied on interior of cylinder in the radial direction by using a coordinate system (ANSYS 14.5 User Guide).

In addition, torsion is imposed to the surface of pinhole for upper and bottom padeye to distributes moment "about" (the vector of) an axis curved faces where right-hand rule is applied to determine sense of moment.

Remote displacement applied to the surface of bottom padeye's pinhole as a boundary condition allows displacements and rotations application at an arbitrary remote location in space. The origin of remote location can be specified under scope in details view by selecting or entering the XYZ coordinates. The default location is at the centroid of the geometry. These remote boundary conditions are all based on the use of a remote point, be it created by the boundary condition itself, or by being scoped to Remote Point object (ANSYS 14.5 User Guide).

Details of loading are as specified in Table 5.

Table 5. Detail of loading condition for each of SB

Items	**Type 1**	**Type 2**	**Type 3**
Horizontal Force (N)	10035.39	9679.53	10498.02
Vertical Force (N)	18149.11	30248.52	30248.52
Lateral Force (N)	1036.94	1587.98	1600.92

Note:
Loadings are derived from rigging arrangement as shown in Figure 1. The maximum loading in upper sling is separated into horizontal (parallel to longitudinal axis of SB) and vertical component. Latera load is assuming 5 percent of DSL.

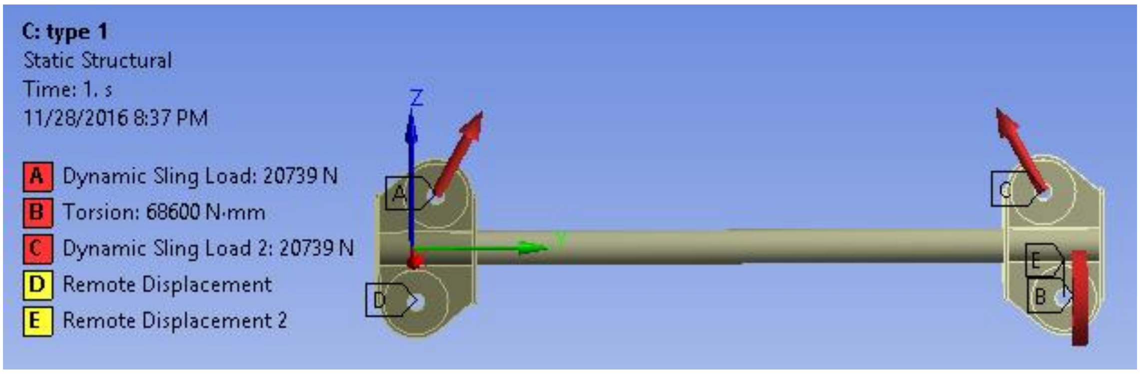


Figure 8 (a). Loading and boundary condition applied to the SB type 1

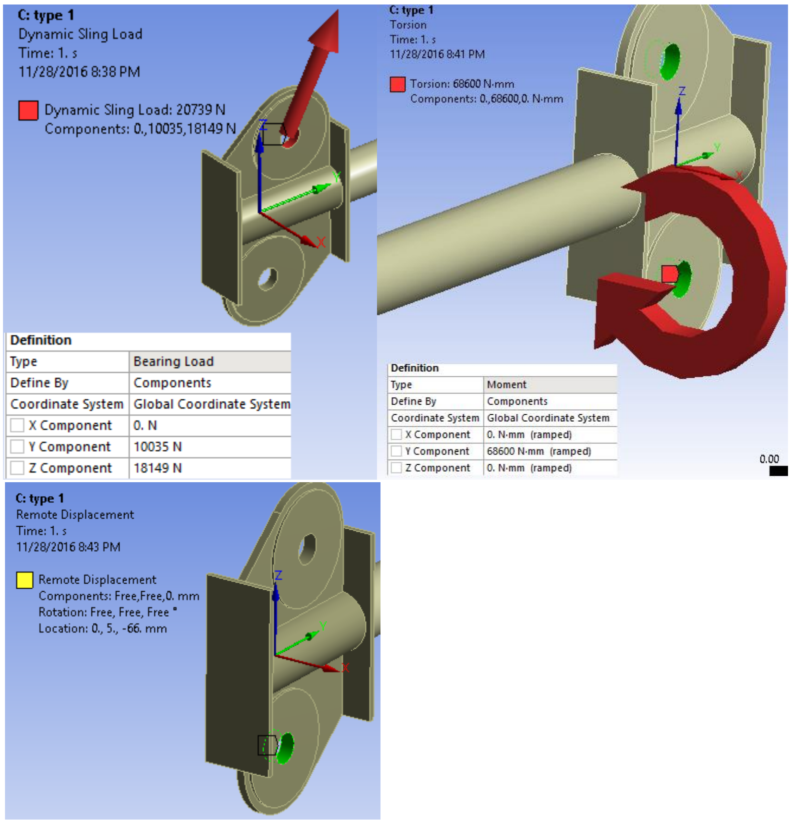


Figure 10(b). Detail of loading condition and boundary condition applied to the SB type 1

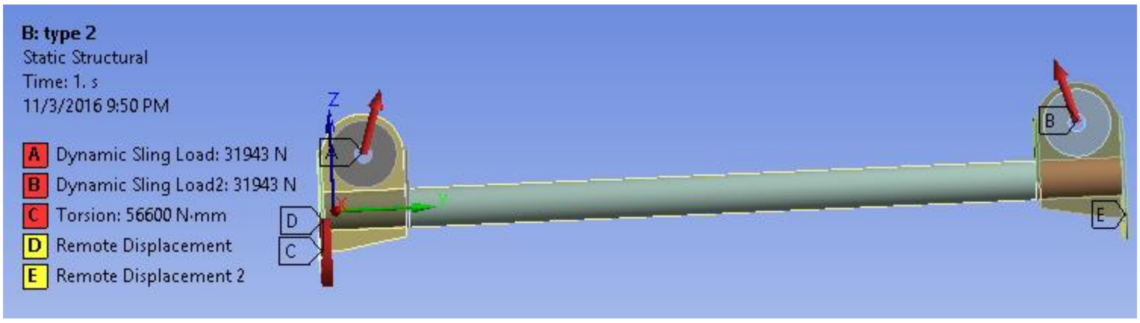


Figure 9 (a). Loading and boundary condition applied to the SB type 2

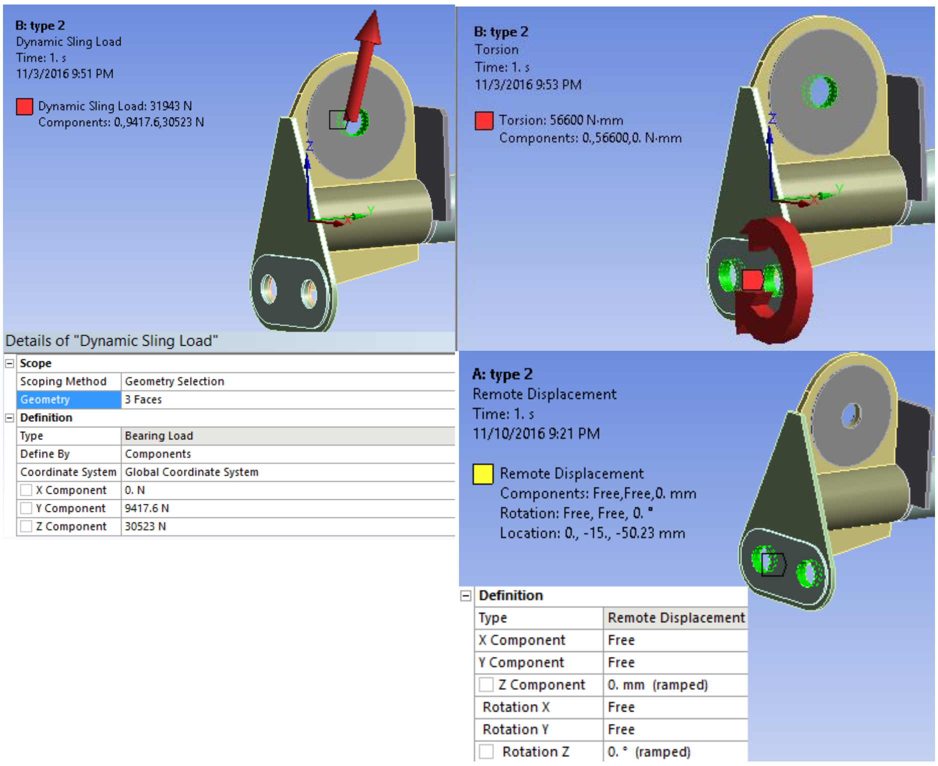


Figure 11(b). Detail of loading and boundary condition applied to the SB type 2

Figure 10 (a). Loading and boundary condition applied to the SB type 3

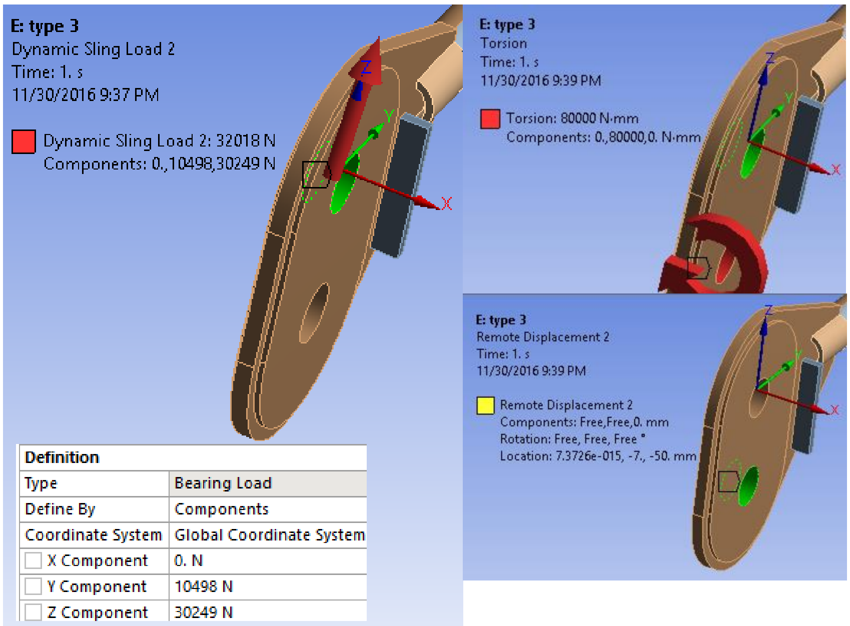


Figure 12(b). Detail of Loading and Boundary Condition applied to the SB type 3

Once stress result is found, linearization of stress is performed. The linearized stress results calculate membrane, bending, peak, and total stress along a straight-line path in the ANSYS workbench. When result is evaluated (stress linearization), component stress values at the path points are interpolated from appropriate element's average corner nodal values. Stress components through the section are linearized by a line integral method and are separated into constant membrane stresses, bending stresses varying linearly between end points, and peak stresses (defined as differences between actual (total) stress and membrane plus bending combination). The details view shows membrane, bending, membrane + bending, peak, and total stresses. The bending stresses are calculated such that neutral axis is at midpoint of the path. Principal stresses are recalculated from the component stresses and are invariant with the coordinate system as long as stress is in the same direction at all points along the defined path (ANSYS 14.5 User Guide).

4.0 EXPERIMENT

The objective of the testing program is to determine critical buckling loads for tubular under compressive force which conducted according to ASTM E9. Only tubular pipe for SB type 3 is used in the experiment. In total, 5 specimens are used in this testing.

Figure 11. Experiment set-up

5.0 RESULTS AND DISCUSSIONS

The tubular size selected as in Table 1 is based on loading applied to the SB structure. Due to huge moment for SB type 2, bigger diameter needs to be selected. Total weight of SB type 1 and 2 are more than 50 percent heavier than SB type 3. The weight ratios (SB's weight/weight of lifted structure) are 0.30, 0.41 and 0.15 percent for SB type 1, 2 and 3 respectively. The differences in sling loads for SB type 1 and 2 are due to the eccentricity of padeyes (Figure 5) where eccentricity is varying on padeye's arrangement (Figure 2). For SB type 1 and 2, the eccentricities are 10mm and 30mm respectively. No eccentricity should be considered for SB type 3 since the CL of top padeye lay at similar line with CL of tubular pipe. SB type 2 having a biggest eccentricity is since delta plate arrangement requires it to be installed far away from upper padeye to ensure that it will not clash with shackle that was installed at the top of padeye. Therefore, padeye type 2 produce highest moment among other types of SB thus require thickest material in design.

The buckling load as specified in Equation (6) is depending upon geometry and elastic modulus of column and not upon the strength of it. However, in AISC ASD, 9th Edition, the equations for allowable compressive stresses, various imperfections such as effect of residual stresses, the actual end restraint conditions, crookedness, and small unavoidable eccentricities are empirically taken into account. To get a buckling stress, buckling load is divided by area of cross section. Considering that buckling stress is found as above, it is noted that allowable compressive stress is fall beyond elastic region for type 1 and 2

of the SB therefore, buckling load did not applied since excessive yielding occurs before reaching the buckling.
For type 1, maximum moment allowed is 5.49E+05N.mm which equivalent to 75 percent of tubular yield strength. Design moment is 2.24E+05N.mm which at 41 percent of allowable moment (based on API 2A Stress Criteria). The maximum moment allowed is 1.19E+06N.mm which equivalent to 75 percent of pipe strength. Design moment is 9.93E+05N.mm which at 84 percent of allowable moment. Therefore, by using SB type 1, 31 percent of the pipe strength is used to resist bending moment while for SB type 2, 63 percent of the pipe strength is used to resist bending moment.

FEA is performed to obtain the Von-Mises stress. The stress linearization is performed for each type of SB to separate primary (structural) and secondary (geometry) stress.

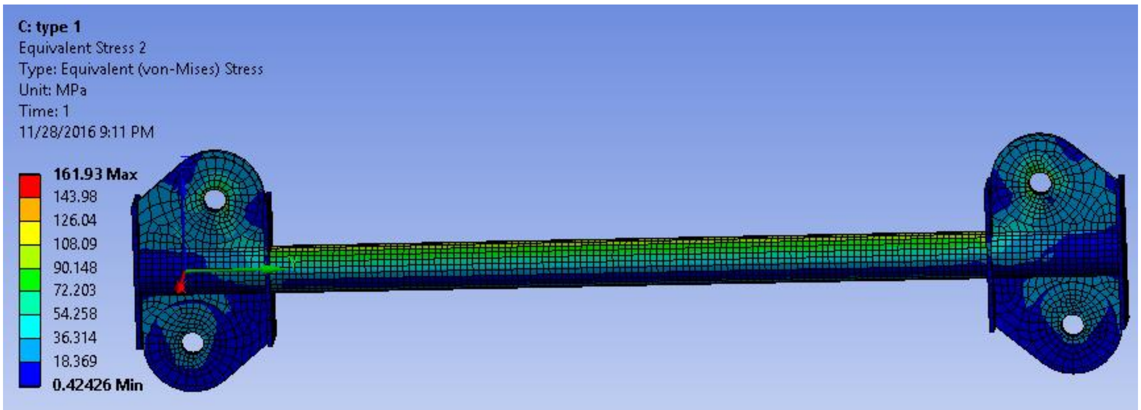


Figure 12 (a). Von-Mises stress for SB type 1

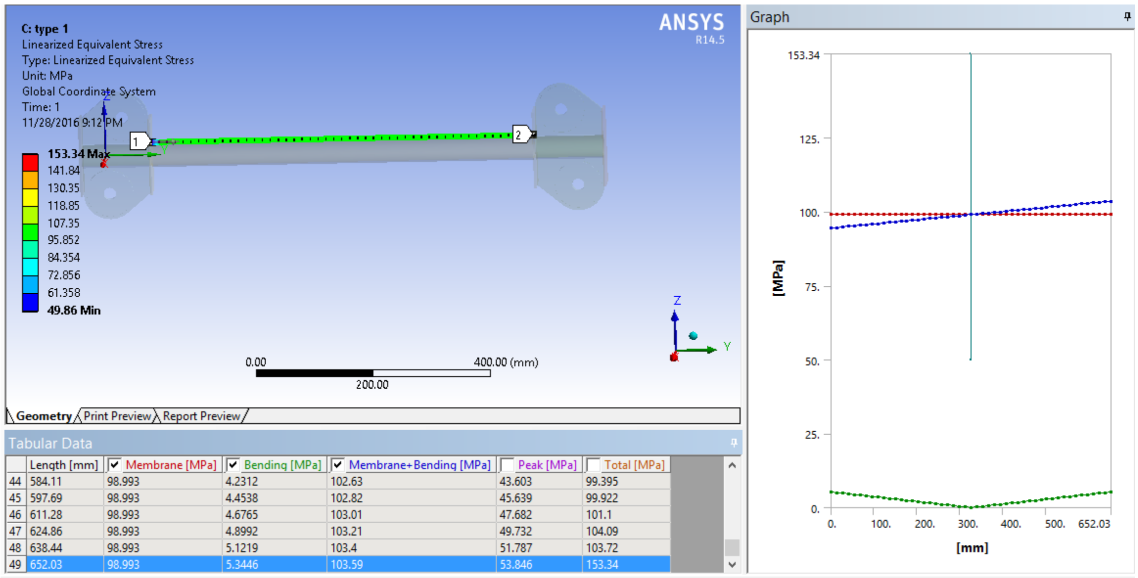


Figure 14(b). Stress linearization for SB type 1

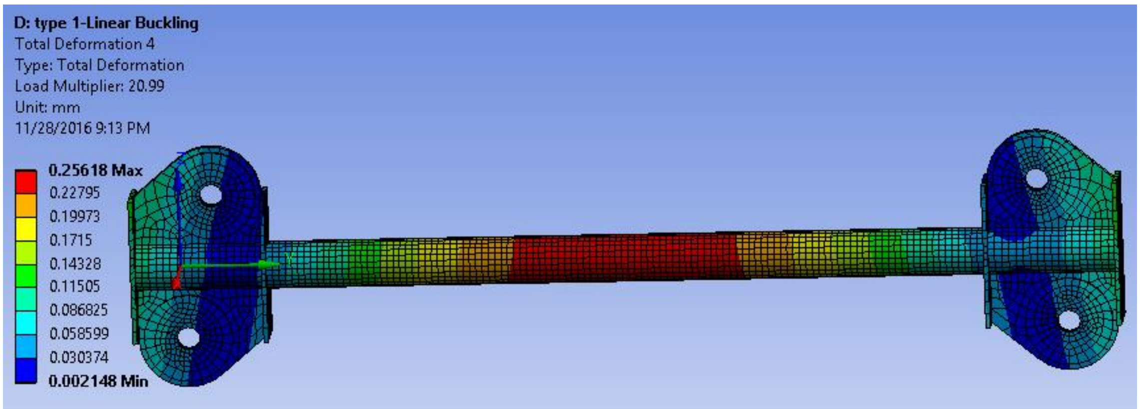


Figure 14(c). Buckling load for SB type 1

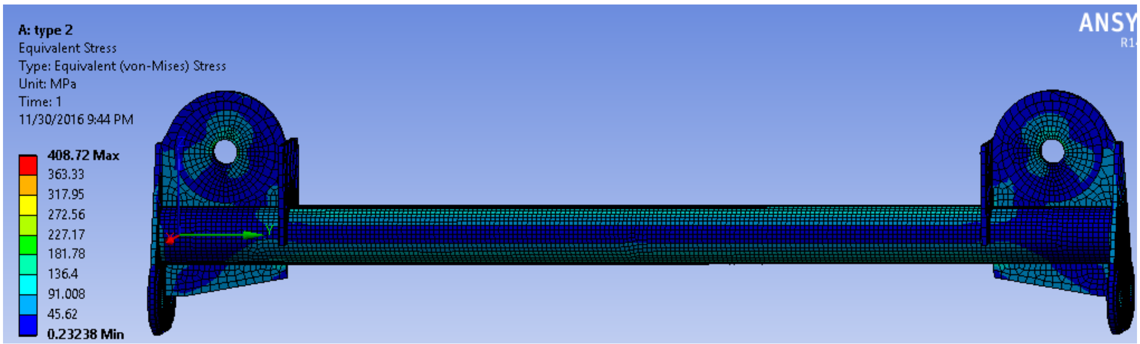


Figure 13 (a). Von-Mises stress for SB type 2

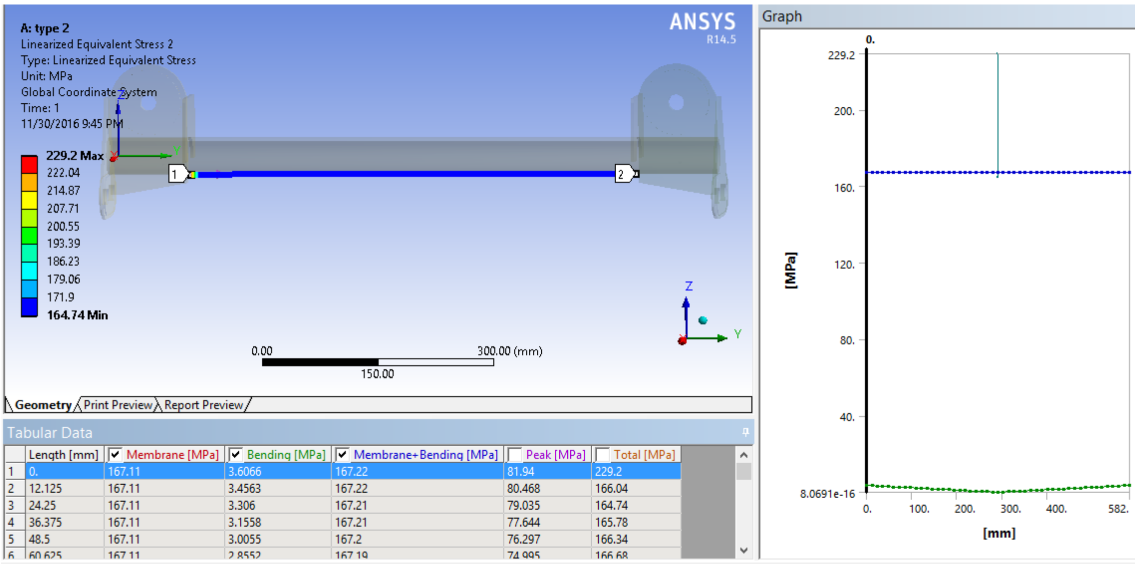


Figure 15(b). Stress linearization for SB type 2

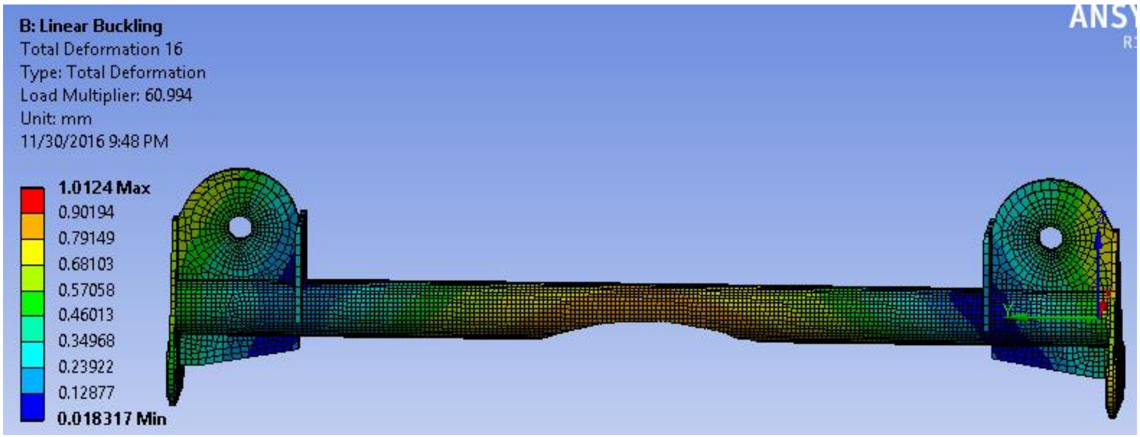


Figure 15(c). Buckling load for SB type 2

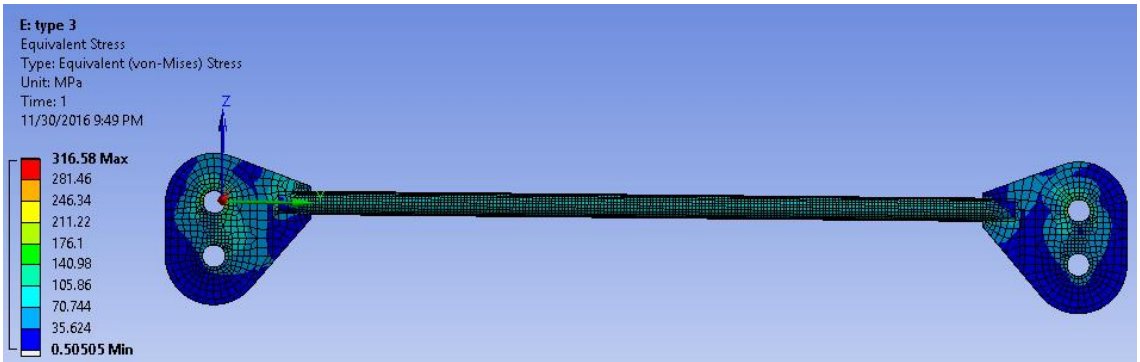


Figure 14 (a). Von-Mises stress for SB type 3

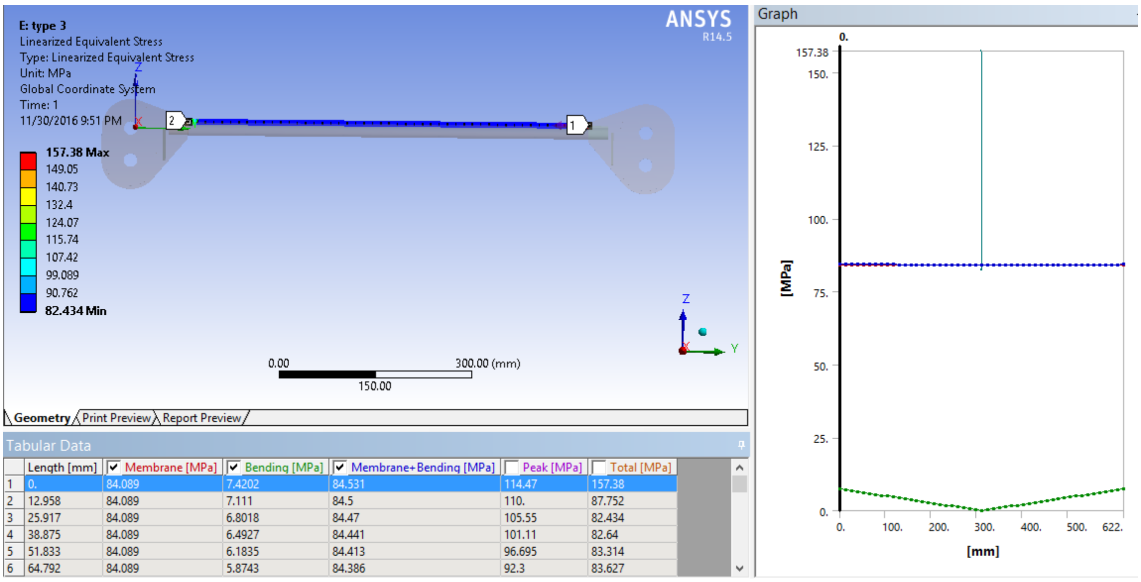


Figure 16 (b). Stress linearization for SB type 3

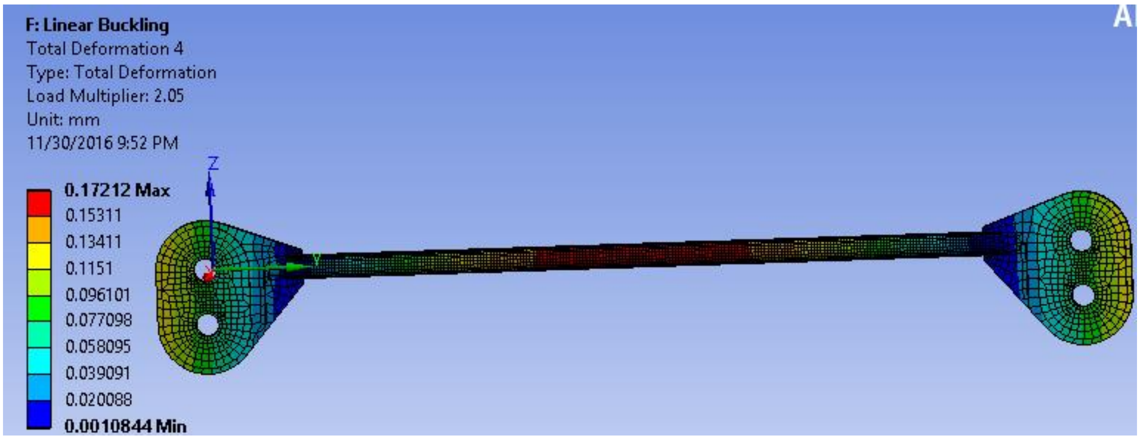


Figure 16(c). Buckling load for SB type 3

As shown in Table 6, mathematical modelling for value of stress is consistent with FEA analysis.

Table 6. Von-Mises stress on tubular

SB Type	Von-Mises Stress (MPa)		
	Theory	**FEA**	**Percentage of Different (%)**
Type 1	106.80	103.59	3
Type 2	170.43	167.22	1.9
Type 3	85.82	84.5	1.5

The experiment results for 5 specimens of pipe used to design SB type 3 shows that the pipe will be buckled at an average load of 23447.12N.

Table 7. Buckling load for specimens of SB type 3

Specimen	Buckling Load (N)
S1	23781.80
S2	22128.31
S3	24368.38
S4	26203.11
S5	20754.02

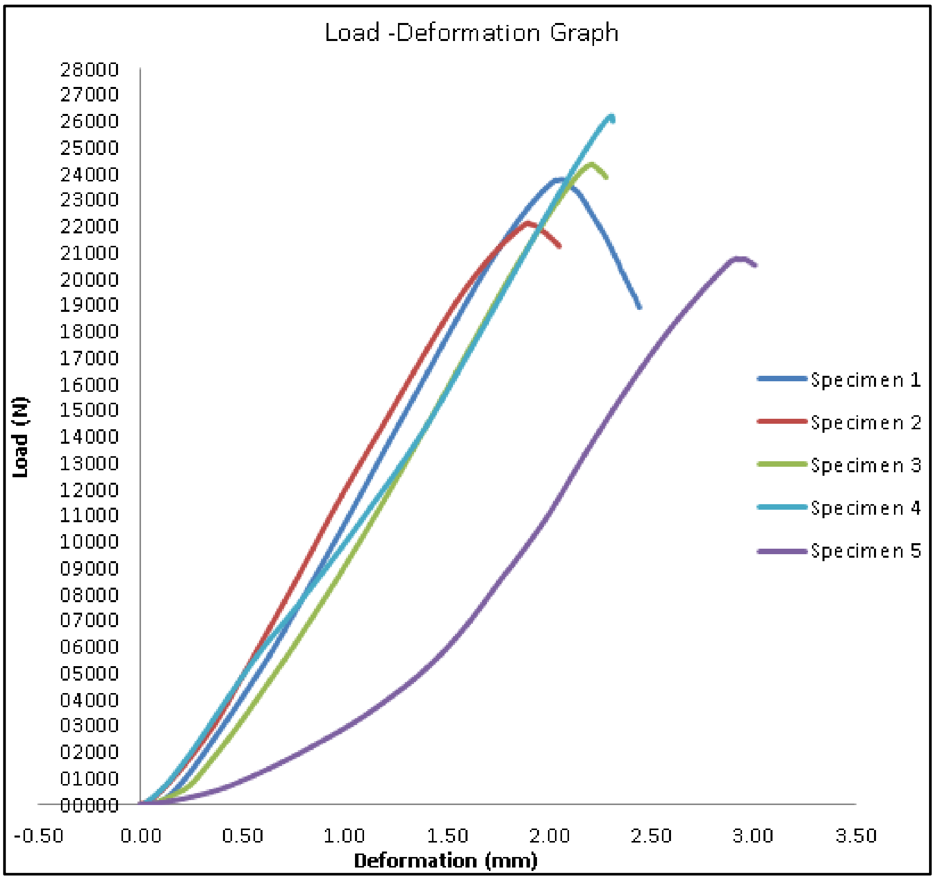


Figure 15. Buckling load for SB type 3 (Experiment)

Table 8. Buckling load and stress for tubular

SB	Buckling Load (N)			Buckling Stress (MPa)			Yield Stress (MPa)
	Theory	FEA	Experiment	Theory	FEA	Experiment	
Type 1	209349.03	210642.90	NA	643.97	647.95	NA	240
Type 2	515899.66	590393.07	NA	772.20	883.70	NA	240
Type 3	22914.11	21520.93	23347.80	142.10	133.46	149.23	240

Table 9. Axial stress for tubular

SB Type	Design Axial Stress (MPa)	Allowable Axial Stress (MPa)
Type 1	30.87	119.68
Type 2	14.49	122.51
Type 3	65.10	72.44

Result as shown in Table 9 indicate that for SB type 1, the utilization of axial stress is only 26 percent of allowable while type 2 is only 12 percent. Remaining tubular pipe strength is used to resist design stress due to bending moment. For SB type 3, the utilization of axial stress is at 90 percent capacity.

Table 10. Details of lifting point geometry on SB

Padeye	**Characteristic**	**Advantage**	**Disadvantage**
Type 1	- CL of upper and bottom padeyes at a distance from CL of tubular. - Top and bottom padeye at a horizontal distance.	Only 2 shackles required.	- Moment due to eccentricity will reduce capacity of tubular. - Bottom shackle require bigger capacity due to de-rated capacity when pulling at certain angle from vertical axis of shackle. By increasing the size of shackle, the size of padeye will increase to accommodate shackle geometries.
Type 2	- CL of upper padeye at a distance from CL of tubular. - Upper and bottom padeye at a horizontal distance. - End plate using delta plate to connect two shackles at bottom padeye.	Smaller shackles used for bottom padeye due to shackle capacity are not required to be de-rated thus reduce the size of padeye.	- Delta plate is installed away from upper padeye to avoid clashed with upper shackle, thus moment due to eccentricity will be higher compared to type 1 and 2 thus reduce the capacity of tubular. - 3 shackles required - More material required to fabricate delta plate. - More welding jobs.
Type 3	- CL of upper padeye at similar elevation of tubular CL.	No moment due to eccentricity, therefore reduce the thickness of tubular. Only 2 shackles required.	- Padeye main plate must check for axial buckling due to horizontal load. - Bottom shackle require bigger capacity due to de-rated while pulling at certain angle from vertical axis of shackle. By increasing the size of shackle, padeye's size will vary to accommodate the shackle geometries.

6.0 CONCLUSIONS

Since SB type 1 and 2 are not categorised as long column as shown in Figure 7, its failure is mainly caused by excessive yielding instead of buckling. Therefore, SB type 1 and 2 is considered as not buckling sensitive. SB type 1and 2 use respective 31 and 63 percent of the pipe strength to resist bending moment which resulting in heavier section needed to be used. Weight of SB type 1 and 2 are more than 50 percent heavier compared to SB type 3. Due to highest moment induced for SB type 2, it is not recommended for used on heavy lifting since thicker material and relatively more welding works and Non-Destructive Test) NDT are required that may increase chances for cracks in the weldment or plate. The moment induced in SB type 1 and 2 resulted in increased of length slot that require more filler material for welding and therefore increase chances of having crack in the structure.

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