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	JOB:		
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DP&T-SRGE	TITLE: **GUIDELINES FOR DROPPED OBJECT STRUCTURE ANALYSIS**		NP-1
			ESUP

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SUMMARY

1 INTRODUCTION

1.1 The aim of this document is to present a technical orientation for the accidental dropped object analysis for FPSO topside modules.

1.2 The content indicated hereafter does not exclude the orientation provided by the Classification Society (CS). Any unfavorable deviation between the information provided by this document and the Classification Society rules must be reported to PETROBRAS.

2 REFERENCE DOCUMENTS

[1] API RP 2A WSD 22th ed. Recommended Practice for Planning, Designing and Constructing – Fixed Offshore Structure;

[2] NORSOK N-004 Design of Steel Structure;

[3] DNVGL-OS-C102 Steel Design of Offshore Ships;

[4] DNVGL-OS-C101 Design of Offshore Steel Structure, General (LRFD Method);

[5] DNVGL-RP-C204 Design Against Accidental Loads;

[6] ISO 19902 Fixed Steel Offshore Structure;

[7] ABS – Accidental Load Analysis and Design for Offshore Structure;

[8] DNVGL-RP-C208 Determination of Structural Capacity by Non-linear Finite Element Analysis Methods;

[9] Salmon, C.G. and Johnson J.E.: Steel Structures Design and Behavior, 4th Edition 1996.

3 DESIGN PREMISSES

3.1 The dropped object structural analysis shall be preceded by mechanical handling and safety studies.

3.2 The initial data required for structural analysis shall be obtained from the safety study, issued by the safety discipline, which shall contain at least the following information:

- ✓ Impact scenarios;
- ✓ Impact energy;
- ✓ Object weight;
- ✓ Height of the falling object;
- ✓ Impact angle;
- ✓ Additional performance criteria;
- ✓ Object shape and dimensions;

3.3 In absence of specific information provided by Classification Society or safety studies, the minimum value for the impact incidence angle shall be 10º in relation to the vertical for critical areas definition.

3.4 The impact area must be selected according to risk assessments and the impact force shall be applied at the most critical positions of the structure for each scenario.

4 DESIGN CRITERIA

4.1 The structural analysis shall be performed in accordance with the conditions indicated in items 4.2 and 4.3.

4.2 Impact Condition (IC)

4.2.1 Impact condition is characterized by the evaluation of the structure local capacity to absorb the impact of a falling object.

4.2.2 A representative finite element model shall be created for the impact condition provided that its extension captures the actual behavior of the structure and since the boundary conditions applied to the model do not affect the results. The modeling might be restricted to a local area but if necessary, the global overall performance of the topside structure shall be assessed with the complete model.

4.2.3 In this step the damaged structural elements may be mapped so that the effect on the overall structure model can be evaluated. The final damaged extension shall be included in the design report.

4.3 Post-Impact Condition (PIC)

4.3.1 The post-impact condition analysis aims to evaluate the overall stability of the structure by considering the presence of damaged structural members. The purpose of this action is to evaluate the strength of the damaged module structure in the in-place condition. This analysis shall be evaluated only after a real accidental event and need not be considered during the design phases.

4.3.2 A global structure finite element model shall be performed for post-impact analysis condition. The damaged members mapped after the accidental event must be simulated in the global structural model and they shall be represented by their correct stiffness. Alternatively, members that have exceeded the yield limit may be removed from the structural model.

4.4 Impact and post-impact conditions may be carried out through simplified analytical limit analysis, linear analysis (static or dynamic) or non-linear analysis (static or dynamic), in ascending complexity order. Structural reinforcement will only be accepted if nonlinear finite element analysis has been carried out.

4.5 The effect of geometric nonlinearity (large deflection) and material nonlinearity (elastic-plastic curve of the material) must be considered for non-linear analysis option.

4.6 Material bi-linear curve may be adopted in non-linear analysis. In the absence of specific information, the curve parameters from DNVGL-RP-C204 [5] as shown in Table 1 shall be used as reference. Alternatively multi-linear curve may also be used as indicated in DNVGL-RP-C208 [8].

Table 1 – Material Properties

Steel yield stress	Critical strain (fracture)	Hardening parameter (H)
235 MPa	20%	0.0022
355 MPa	15%	0.0034
460 MPa	10%	0.0034

4.7 Rupture is assumed to occur when the tensile strain due to the combined effect of rotation and membrane elongation exceed the critical value as per Table 1.

4.8 The analysis shall be performed considering the load combination as indicated in Table 2.

Table 2 – Accidental Loads Combination

Nature of load	Analysis Condition	
	Impact * (IC)	Post Impact (PIC)
Static	yes	yes
Functional overloads	yes	yes

Environmental (wave and wind)	no	yes
Accidental (dropped object)	yes	no
* Care shall be taken for the load sequence on the non-linear analysis. The impact load must be applied after the permanent loads (static and functional).		

4.9 The return period for the environmental loads shall be 10 years. This assumption considers that the structure will be repaired in due time.

4.10 The functional overloads for the impact condition (IC) must be applied on storage and laydown areas only, disregarded for other areas.

4.11 The allowable stresses for linear analysis may be increased in impact and post impact conditions by factor 1.67 (WSD).

5 SIMPLIFIED ANALYTIC LIMIT METHOD

5.1 The simplified analytic limit method of frame structures considers the formation of mechanism (plastic hinges) to be used for the impact condition (IC) evaluation. The specific criteria indicated in the next items must be observed. Two design examples are also presented in item 7 for reference only.

5.2 The impact force calculation can be deduced from the concept of energy conservation by assuming that the object is rigid, and the kinetic energy is fully transformed into strain energy in the structure.

5.3 The kinetic energy is given by equation 01 below:

$$Ec = \frac{1}{2} \times m \times v^2 \qquad \text{(EQ -01)}$$

Where:

m = mass of object in air;

v = impact speed.

5.4 The impact speed of the object in the air is given by equation 02:

$$v = \sqrt{2 \times g \times h} \qquad \text{(EQ -02)}$$

Where:

g = acceleration of gravity;

h = height of fall.

5.5 Based on the kinetic energy and the structural stiffness in the direction of impact application it is possible to deduce the impact force using linear analysis. To do so, it is necessary to obtain the displacement of the structure by equating the kinetic energy with the elastic potential energy and thus obtain equation 03.

$$Ec = \frac{1}{2} \times m \times v^2 = Ep = \frac{1}{2} \times k \times \Delta^2 \qquad \text{(EQ -03)}$$

Where:

k = structure stiffness on the direction of the impact application force (the stiffness may be taken from the structural model by applying a unity force. It shall be documented);

Δ = structure displacement on the direction of the impact force;

Ep = Elastic potential energy.

5.6 The unknown variable from the equation 03 is the displacement. By putting this variable in evidence, it is possible to obtain the impact force through the Hooke's law.

5.7 The procedure indicated in items 5.5 and 5.6 may only be used if the stresses produced by the impact force do not exceed the material yield limit. The local buckling must also be investigated since it may control the design for non-compact and slender sections. In this case, the maximum buckling elastic energy shall be evaluated. In other words, the structural element shall be classified as compact.

5.8 The structure model shall be idealized as a simple beam supported at the ends. In this case, the plastic hinge takes place at the middle of span and at the same position of the impact load.

5.9 The entire impact energy is supposed to be absorbed by the internal strain energy due to bending. The material behavior at the transition phase can be considered as linear extension until M_y (elastic moment) reaches M_p (plastic moment), according to the reference [9]. See Figure 1 for better understanding.

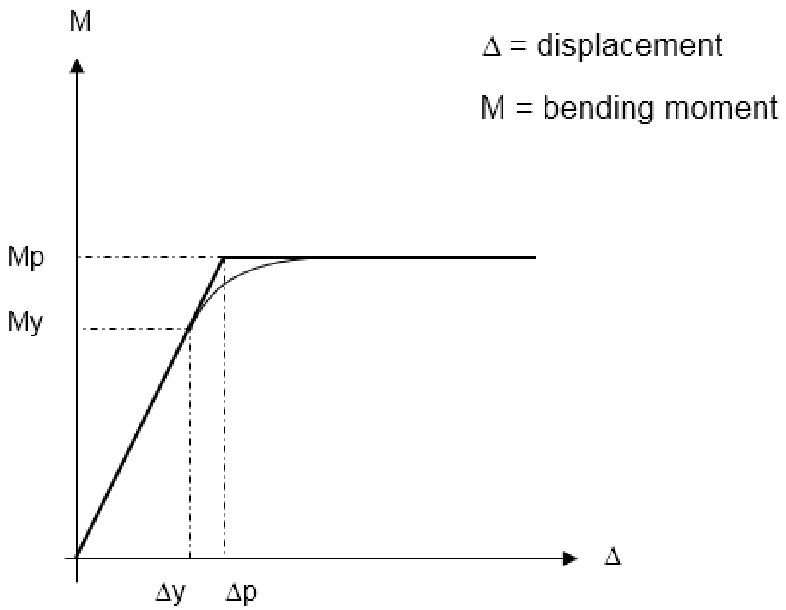


Figure 1 – Material Behavior for Plastic Hinge Analysis

5.10 The beam span must be selected in a coherent manner by using the same criteria for the maximum displacement evaluation.

5.11 The simplified analytic limit method cannot be used for final non acceptance of the structure. In case this criterion is not met, the designer shall use advanced analysis techniques with appropriate engineering software.

6 ACCEPTANCE CRITERIA

6.1 The safety critical equipment and other critical elements, as defined by the safety discipline, shall remain intact after the accidental event. In order to meet this criterion, the results of dropped object analysis shall be evaluated together with the impacted disciplines.

6.2 The damage extension shall be restricted to the topside structure at the main elevation where the impact is supposed to occur which shall absorb all the impact energy. Therefore, the object cannot reach the hull structure components during the impact event.

6.3 The global structure stability shall be preserved. Local rupture is not allowed for primary structures. The result of impact condition analysis is acceptable for primary structures when the final strain result is less than plastic strain limit indicated in Table 1.

6.4 The local failure of secondary structures is permitted provided that the items 6.1 to 6.3 be satisfied. For laydown areas it may be considered the favorable effect of the wood/timber for the stress distribution.

6.5 For a real accidental event, the designer shall satisfy the post impact criteria as indicated in item 4 in accordance with the contractual rules to prevent the global module structure failure and the event escalation until repair is carried out.

6.6 The analysis will be considered complete for the impact condition when the assessment process depicted on the Figure 2 is utterly satisfied. For the post impact assessment, the process depicted on the Figure 3 shall be satisfied.

6.7 Others specific criteria indicated in the safety study issued by the Safety discipline must be met in the structural analysis and therefore shall be considered as a complementary part of these guidelines.

6.8 If the analysis result does not meet the acceptance criteria, the designer must propose and define the engineering solution, giving special priority to the mitigation of the risk factors. The engineering solution must be submitted to and approved by PETROBRAS when the structure reinforcement is an option. In any case, this kind of solution shall be avoided for design phases.

6.9 The structural designer shall inform in the final report the level of impact energy that each topside structure resists for the worst scenarios in order to reassess the actual impairment probability, regardless of results.

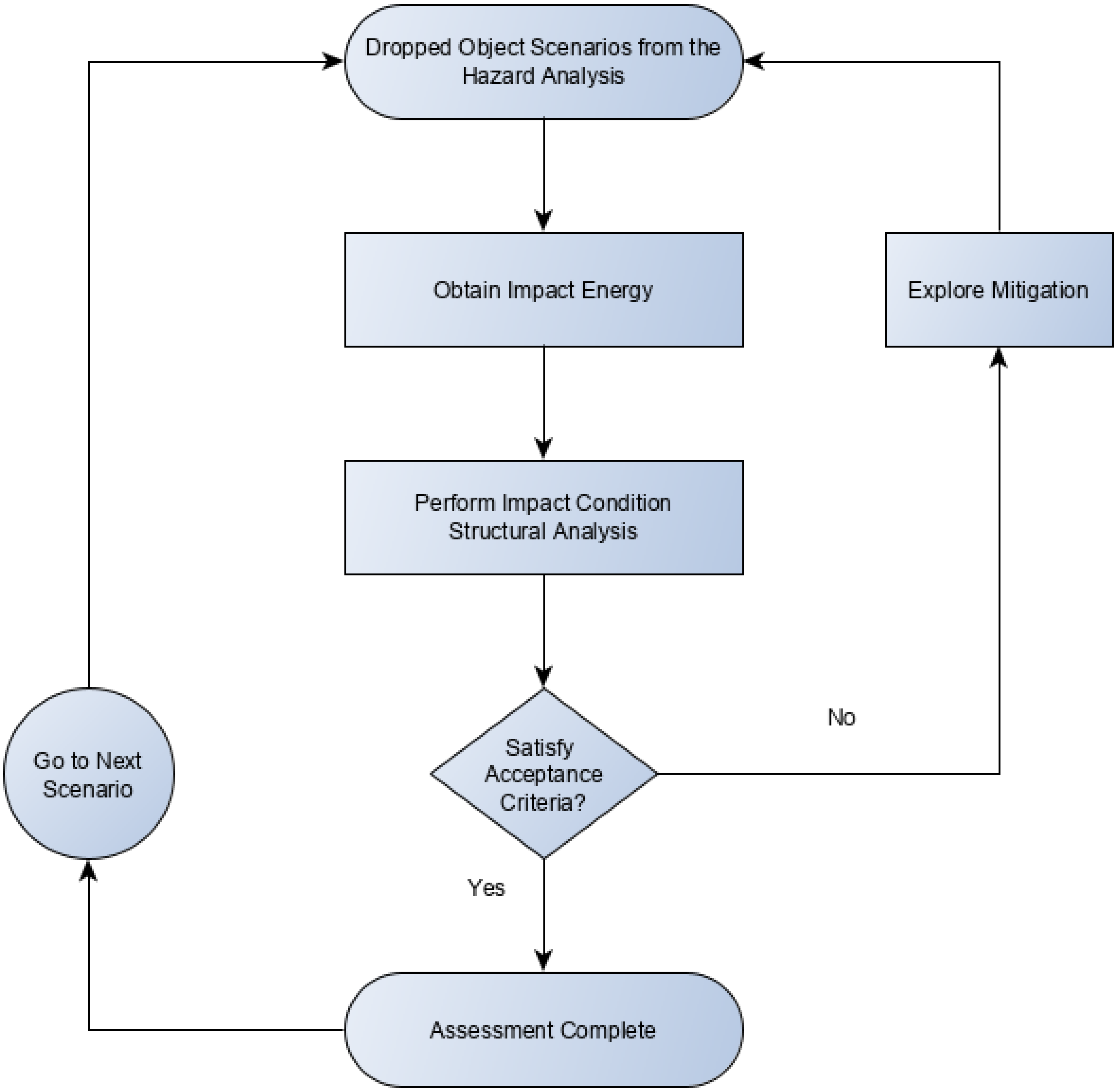


Figure 2 – Impact Condition Assessment Process

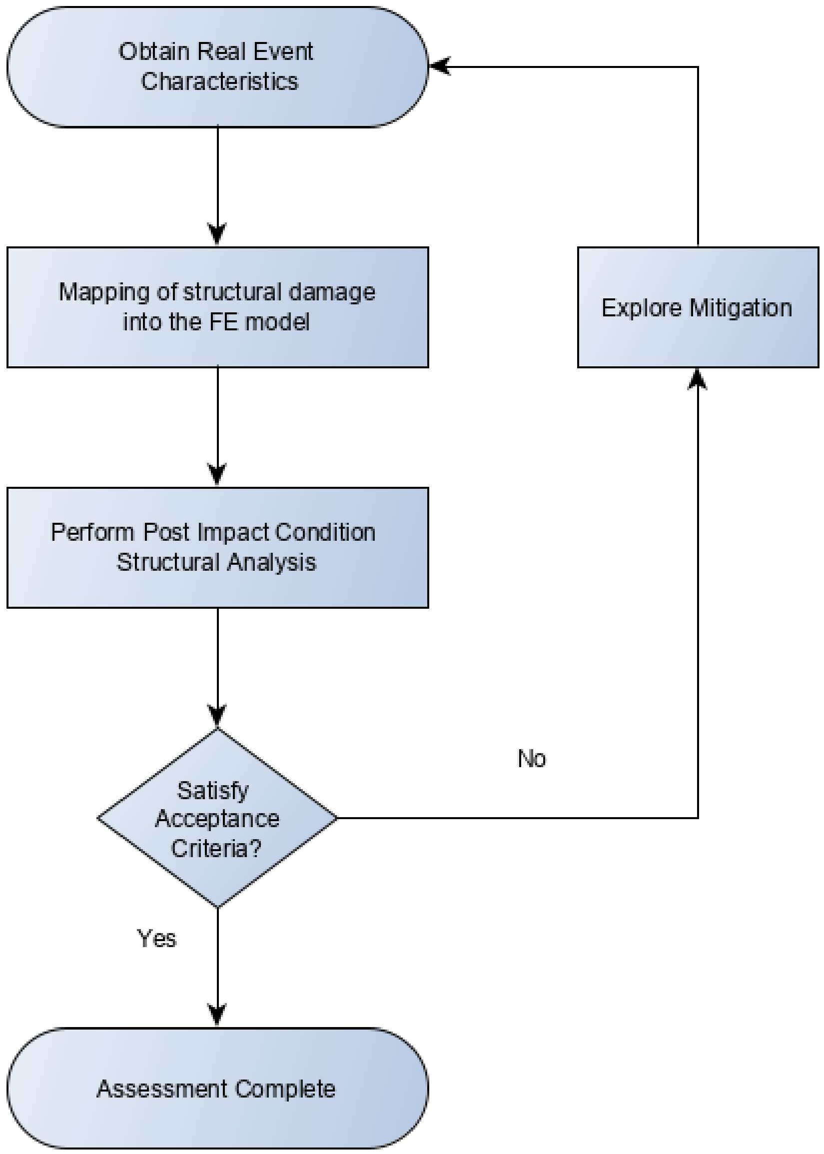
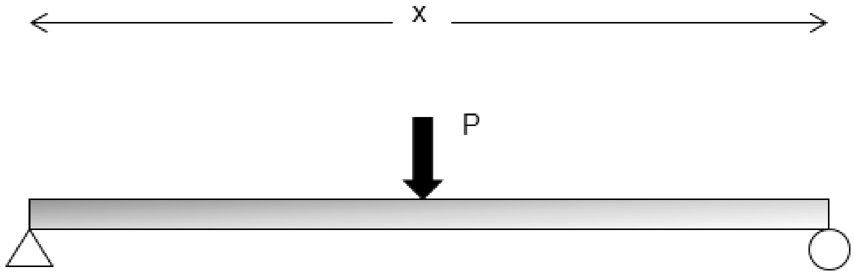


Figure 3 – Post Impact Condition Assessment Process

7 DESIGN EXAMPLE

Let us check a rolled beam W 530x92 undergoing an impact load on the middle of span from a falling object. The beam has 7,315m of span and it is simply supported at the ends. Only the impact load is considered on this example. For a real design check, it shall be considered the loads combination as indicated on table 1. Note: assume in this example that there is no lateral torsional and local buckling (compact section).



Given:

Mass of the object: $mass := 100kg$

Acceleration of gravity: $g = 9.807\frac{m}{s^2}$

Height of fall: $h := 2m$

Moment of Inertia: $I := 55157cm^4$

Section modulus: $w := 2069.7cm^3$

Plastic Modulus: $Z := 2359.8cm^3$

Beam span: $x := 7.315m$

Modulus of Elasticity: $E := 200000\frac{N}{mm^2}$

Yield stress limit: $F_y := 248.2\frac{N}{mm^2}$

Distance from the neutral axis to the extreme fiber: $c_z := 266.5mm$

A) Kinetic energy calculation:

$$v := \sqrt{2 \cdot g \cdot h} = 6.263 \frac{m}{s}$$

$$E_c := \frac{1}{2} \cdot mass \cdot v^2 = 1961.33\,J$$

B) Stiffness calculation

$$P := 1N$$

$$\delta_{unity} := \frac{P \cdot x^3}{48 \cdot E \cdot I} = 7.392 \times 10^{-8}\,m$$

$$k := \frac{1 \cdot N}{\delta_{unity}} = 1.353 \times 10^{7} \cdot \frac{N}{m}$$

C) Total displacement due to the impact load

$$E_p := E_c$$

$$\Delta := \sqrt{\frac{2 \cdot E_p}{k}} = 0.017 \cdot m$$

D) Equivalent impact force (Hooke's Law)

$$F_r := k \cdot \Delta = 230.359 \cdot kN$$

E) Maximum allowable elastic displacement

$$\Delta_e := \frac{F_y \cdot x^2}{12 \cdot c_z \cdot E} = 0.021 \cdot m$$

Conclusion:

The maximum elastic displacement (Δ_e) is greater than the total displacement due to the impact load (Δ). Therefore, the bending stress do not reach the plasticity and the structure can be considered acceptable. No further analysis needs to be done.

Now, let us consider the same example with the modification on the height of the fall (4m) and the mass of the object (500kg).

Given:

Mass of the object: $mass := 500kg$

Acceleration of gravity: $g = 9.807 \frac{m}{s^2}$

Height of fall: $h := 4m$

Moment of Inertia: $I := 55157cm^4$

Section modulus: $w := 2069.7cm^3$

Plastic Modulus: $Z := 2359.8cm^3$

Beam span: $x := 7.315m$

Modulus of Elasticity: $E := 200000 \frac{N}{mm^2}$

Yield stress limit $F_y := 248.2 \frac{N}{mm^2}$

Distance from the neutral axis to the extreme fiber: $c_z := 266.5mm$

A) Kinetic energy due to the dropped object:

$$v := \sqrt{2 \cdot g \cdot h} = 8.857 \frac{m}{s}$$

$$E_c := \frac{1}{2} \cdot mass \cdot v^2 = 19613.3J$$

B) Stiffness for a force applied at middle of span

$$P := 1N$$

$$\delta_{unity} := \frac{P \cdot x^3}{48 \cdot E \cdot I} = 7.392 \times 10^{-8} m$$

$$k := \frac{1 \cdot N}{\delta_{unity}} = 1.353 \times 10^{7} \cdot \frac{N}{m}$$

C) Total displacement due to the impact load

$$E_p := E_c$$

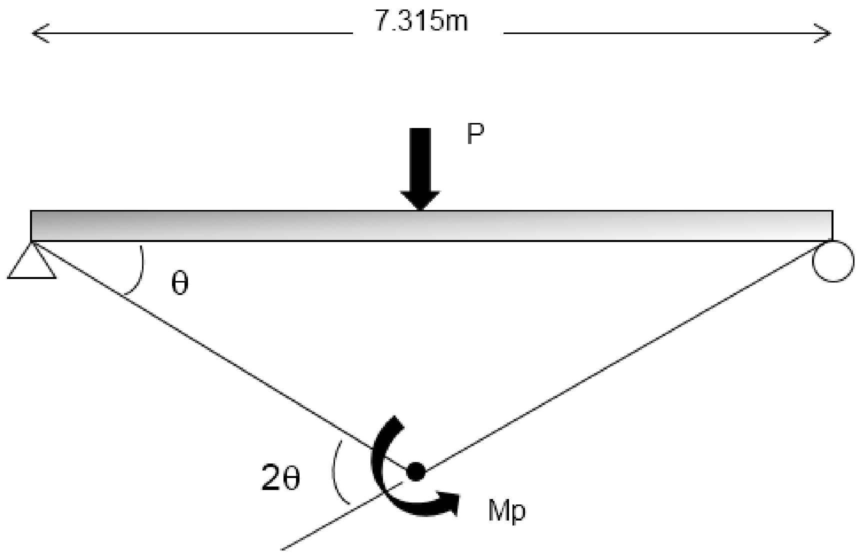
$$\Delta := \sqrt{\frac{2 \cdot E_p}{k}} = 0.054 \cdot m$$

The displacement (Δ = 0.054) was assumed to be completely absorbed by the structure in the elastic domaim. However, for this assumption validation it is necessary to check if the maximum elastic displacemet (Δ_e) is greater than Δ **.** This comparison is presented in the next item.

D) Maximum elastic displacement

$$\Delta_e := \frac{F_y \cdot x^2}{12 \cdot c_z \cdot E} = 0.021 \cdot m$$

The calculated displacement Δ = 0.054 m is greater than the maximum elastic displacement Δe = 0.021 m. Therefore, linear analysis cannot be used since the stress exceeded the elastic phase. From now, the hinge formation analysis is used by considering the material as elastic - perfectly plastic and the plastic hinge formation at the middle of the span.



E) Elastic and plastic moment calculation

$$M_p := F_y \cdot Z = 585.702\,kN \cdot m$$

$$M_e := F_y \cdot w = 513.7\,kN \cdot m$$

F) Shape factor

$$\xi := \frac{M_p}{M_e} = 1.14$$

G) Total displacement including the elastic and plastic phase

$$\Delta_{tot} := \xi \cdot \Delta_e = 0.024\,m$$

H) Hinge rotation at the middle span

$$\theta := \frac{\Delta_{tot} \cdot 2}{x} = 0.006$$

I) Work done by the moment

Wint: = 0.5.Mp.2.θ = 3514 J

Conclusion:

The maximum energy absorbed by the beam is less than the impact energy. Therefore, a nonlinear analysis must be done to check the structure.