[redacted] Limited

[redacted]

Registered in England & Wales
Company Registration Number [redacted]

[redacted]

Report: [redacted]-R0724-21

KINGS LYNN COMPRESSOR STATION – RESOLUTION OF IGE/TD/12 CODE STRESS EXCEPTIONS

Confidential *Restricted to [redacted], National Grid and [redacted]*

COMPANY ADDRESS:
[redacted]

COMPANY CONTACT DETAILS:
TELEPHONE: [redacted]
E-MAIL:
[redacted]

[redacted]

CUSTOMER	CUSTOMER CONTACT	CUSTOMER ADDRESS	CUSTOMER REF: NO.
[redacted]	[redacted]	[redacted]	
[redacted] PROJECT NO: [redacted]-P0488	**[redacted] REPORT NO:** [redacted]-R0724-21	**[redacted] PROJECT FILE NO:** [redacted]-F0488	**KEYWORDS** STRESS ANALYSIS, IGE/TD/12,

EXTERNAL DISTRIBUTION LIST	COMPANY
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

INTERNAL DISTRIBUTION LIST	LOCATION
Project File	[redacted]-F0488
Library File	Technical Section

01	18/02/22	[redacted]	[redacted]	[redacted]	Accepted
00	16/12/21	[redacted]	[redacted]	[redacted]	Draft for Client Comment
Revision	**Date**	**Author Signature**	**Verifier Signature**	**Approver Signature**	**Status**

[redacted]

REVISION STATUS INDEX							
SUMMARY OF CHANGES	**SECTION NUMBER**	**REVISIONS**					
		1	**2**	**3**	**4**	**5**	**6**

[redacted]

Executive Summary

National Grid owns and operates Kings Lynn Compressor Station in Norfolk. At a part of the site, in the area of the bi-directional pipework, associated with the compressors, there is visible evidence of changes to the ground elevation, suggesting differential settlement.

A previous study, [redacted]-R0706-21, was undertaken to assess the effects of the settlement to the abnormal sustained and shakedown criteria of IGE/TD/12. A small quantity of code stress exceptions were identified during the study.

Additionally, as part of potential site upgrade and remediation works, National Grid propose to demolish three pits onsite and backfill the associated pipework with native ground. Previous studies, [redacted]-R0711-21 and [redacted]-R0713-21, were undertaken to consider the effects of the proposed modifications to the sustained, shakedown and fatigue criteria of IGE/TD/12. A number of IGE/TD/12 code stress exceptions, due to the proposed modifications, were identified.

In total twenty-eight code stress exceptions were identified on six fitting types. Where multiple code stress exceptions exist for a single fitting type then the greater exception is said to 'bound' the lesser. Thus, it is possible to qualify multiple fittings of the same type and classification with a single assessment. To this end a more detailed analysis of the following fittings is required:

- 900mm x 900mm Tee
- 900mm x 90° Bend
- 900mm x 300mm Sweepolet
- 900mm x 200mm Sweepolet
- 900mm x 50mm Weldolet
- 50mm x 50mm Tee

This involves creating a detailed three-dimensional finite element (FE) model of each fitting type, applying the loads on the FE model, analysing the model using finite element analysis (FEA) and then assessing the stresses from the FEA using appropriate design-by-analysis methods, such as that given in IGE/TD/12 Appendix 6.

The purpose of this report is to describe the modelling, finite element analysis (FEA) and results of the assessments that were undertaken to determine the fitness-for-purpose of each fitting type.

[redacted]

Conclusions

1. The 900mm x 900mm tee:

    i. Satisfies the TD/12 global plastic collapse criterion.

    ii. Does not satisfy the local plastic collapse criterion.

    a. A limit load analysis has been performed, for which a limiting load factor of 1.3 was found.

    iii. Does not satisfy the IGE/TD/12 shakedown assessment criterion.

    a. An elastic-plastic ratcheting assessment was performed to the requirements of ASME VIII Division 2. The fitting failed to shakedown to an elastic-plastic load cycle and repeat loadings would eventually lead to incremental plastic collapse.

    b. Shakedown was successfully achieved when considering X65 material grade.

2. The 900mm x 90° bend:

    i. Satisfies the TD/12 limit load analysis criterion.

3. The 900mm x 300mm sweepolet:

    i. Satisfies the TD/12 limit load analysis criterion.

    ii. Satisfies the ASME VIII Division 2 elastic-plastic ratcheting assessment criterion.

    iii. Satisfies the TD/12 fatigue assessment criterion.

4. The 900mm x 200mm sweepolet:

    i. Satisfies the TD/12 limit load analysis criterion.

    ii. Satisfies the ASME VIII Division 2 elastic-plastic ratcheting assessment criterion.

    iii. Satisfies the TD/12 fatigue assessment criterion.

5. The 900mm x 50mm weldolet:

    i. Satisfies the TD/12 limit load analysis criterion.

6. The 50mm x 50mm tee:

    i. Satisfies the TD/12 limit load analysis criterion.

[redacted]

Recommendations

Conservative assumptions have been made on the 900mm x 900mm tee material grade and geometry. It is recommended that material scrapings and geometrical measurements of the fitting are undertaken to determine the actual material grade of the fitting and actual fitting wall thicknesses. If the material grade is shown to be higher than X56 and the fitting is shown to be thicker, then a revised model and analysis would be recommended before considering replacing the tee.

[redacted]

CONTENTS

1 INTRODUCTION **7**
1.1 Purpose **7**
1.2 Scope **8**
2 MODELS AND LOADING **8**
2.1 900mm x 900mm Tee **8**
2.2 900mm x 90°mm Bend **8**
2.3 900mm x 300mm Sweepolet **8**
2.4 900mm x 200mm Sweepolet **8**
2.5 900mm x 50mm Weldolet **8**
2.6 50mm x 50mm Tee **8**
3 ASSESSMENT CRITERIA **8**
3.1 Sustained **9**
3.1.1 General Primary Membrane Stress 9
3.1.2 Local Primary Membrane Stress 9
3.1.3 Local Primary Membrane Plus Primary Bending 9
3.1.4 Limit Load Analysis 9
3.2 Incremental Plastic Collapse – Elastic Stress Analysis **10**
3.2.1 Incremental Plastic Collapse – Elastic-Plastic Stress Analysis 10
3.3 Fatigue **10**
3.3.1 Sweepolets 10
4 RESULTS **11**
4.1 900mm x 900mm Tee **11**
4.2 900mm x 90°mm Bend **11**
4.3 900mm x 300mm Sweepolet **11**
4.4 900mm x 200mm Sweepolet **11**
4.5 900mm x 50mm Weldolet **11**
4.6 50mm x 50mm Tee **11**
5 CONCLUSIONS **12**
6 RECOMMENDATIONS **13**
7 REFERENCES **13**
8 TABLES **14**
APPENDIX A 900MM X 900MM TEE ASSESSMENT **16**
A.6.2.1 GLOBAL PRIMARY MEMBRANE STRESS **17**
A.6.2.2 LOCAL PRIMARY MEMBRANE STRESS PLUS PRIMARY BENDING **18**
A.6.2.3 LIMIT LOAD ANALYSIS **18**
A.6.3.4 SHAKEDOWN - ELASTIC-PLASTIC ASSESSMENT **18**
APPENDIX B 900MM X 90° BEND ASSESSMENT **31**
APPENDIX C 900MM X 300MM SWEEPOLET ASSESSMENT **38**
C.6.1.5 SUSTAINED **39**
APPENDIX D 900MM X 200MM SWEEPOLET ASSESSMENT **62**
D.6.2.6 LIMIT LOAD ANALYSIS **63**
APPENDIX E 900MM X 50MM WELDOLET ASSESSMENT **85**
E.6.2.7 LIMIT LOAD ANALYSIS **86**
APPENDIX F 50MM X 50MM TEE ASSESSMENT **93**
F.6.2.8 LIMIT LOAD ANALYSIS **94**

[redacted]

1 INTRODUCTION

National Grid owns and operates Kings Lynn Compressor Station in Norfolk. At a part of the site, in the area of the bi directional pipework, associated with the compressors, there is visible evidence of changes to the ground elevation, suggesting differential settlement.

A previous study, [redacted] R0706 21 [1], was undertaken to assess the effects of the settlement to the abnormal sustained and shakedown criteria of IGE/TD/12. A small quantity of code stress exceptions were identified during the study.

Additionally, as part of potential site upgrade and remediation works, National Grid propose to demolish three pits onsite and backfill the associated pipework. Previous studies, [redacted]-R0711-21 [2] and [redacted]-R0713 21 [3], were undertaken to consider the effects of the proposed modifications to the sustained, shakedown and fatigue criteria of IGE/TD/12. A number of IGE/TD/12 code stress exceptions, due to the proposed modifications, were identified.

In total twenty-eight code stress exceptions were identified on six fitting types. Where multiple code stress exceptions exist for a single fitting type then the greater exception is said to 'bound' the lesser. Thus, it is possible to qualify multiple fittings of the same type and classification with a single assessment. To this end a more detailed analysis of the following fittings is required:

- 900mm x 900mm Tee
- 900mm x 90° Bend
- 900mm x 300mm Sweepolet
- 900mm x 200mm Sweepolet
- 900mm x 50mm Weldolet
- 50mm x 50mm Tee

This involves creating a detailed 3-dimensional finite element (FE) model of each fitting type, applying the loads on the FE model, analysing the model using finite element analysis (FEA) and then assessing the stresses from the FEA using appropriate design-by-analysis methods, such as that given in IGE/TD/12 Appendix 6.

The purpose of this report is to describe the modelling, finite element analysis (FEA) and results of the assessments that were undertaken to determine the fitness-for-purpose of each fitting type.

1.1 Purpose

The purpose of this report is to describe the modelling, finite element analysis (FEA) and results of the assessments that were undertaken to determine the fitness-for-purpose of each fitting type.

[redacted]

1.2 Scope

This report describes the modelling and fitness-for-purpose assessment of the fittings at Kings Lynn compressor station where code stress exceptions have been identified.

Where relevant, the assessments herein consider the code stress exceptions identified on fittings after removal of the three pits.

2 MODELS AND LOADING

A summary of the fitting types considered herein, including the corresponding pipe stress model, is supplied in Table 1.

Details of the model generation and applied loading for each fitting type are provided in the following sections

2.1 900mm x 900mm Tee

See Appendix A.

2.2 900mm x 90°mm Bend

See Appendix B.

2.3 900mm x 300mm Sweepolet

See Appendix C.

2.4 900mm x 200mm Sweepolet

See Appendix D.

2.5 900mm x 50mm Weldolet

See Appendix E.

2.6 50mm x 50mm Tee

See Appendix F.

3 ASSESSMENT CRITERIA

IGE/TD/12 Appendix 6 gives some guidance on assessing the stress fields generated from finite element analysis. The TD/12 acceptance criteria are used herein.

[redacted]

3.1 Sustained

3.1.1 General Primary Membrane Stress

According to IGE/TD/12 [4], for an AGI in a Type 'R' area the design factor is 0.67, the limit on linearised general primary membrane stress intensity (Tresca), P_m, for normal sustained and abnormal sustained is provided in the table below:

f	Limiting Value of Stress Intensity (S)			
	Normal Sustained		Abnormal Sustained	
	$\frac{SMYS}{UTS} \leq 0.74$	$\frac{SMYS}{UTS} > 0.74$	$\frac{SMYS}{UTS} \leq 0.74$	$\frac{SMYS}{UTS} > 0.74$
0.67	0.8 SMYS	0.34(SMYS+UTS)	0.9(SMYS)	0.34(SMYS+UTS)

Where, SMYS is the Specified Minimum Yield Strength and UTS is the Ultimate Tensile Strength.

3.1.2 Local Primary Membrane Stress

According to IGE/TD/12, the limit on linearised local primary membrane stress intensity (Tresca), P_L, is the lower of:

$$\text{SMYS or } 1.5\left(\frac{\text{UTS}}{2.35}\right) \tag{1}$$

3.1.3 Local Primary Membrane Plus Primary Bending

According to IGE/TD/12, the limit on linearised local primary membrane plus primary bending stress intensity (Tresca), P_L+P_b, is also the lower of:

$$\text{SMYS or } 1.5\left(\frac{\text{UTS}}{2.35}\right) \tag{2}$$

3.1.4 Limit Load Analysis

For instances whereby a fitting does not satisfy any of the above criteria, or suitable stress planes cannot be readily identified for linearisation across a section, a limit load analysis should be performed to the requirements of Section A6.7 of IGE/TD/12.The limit load is defined as the load which causes overall structural instability. This point is indicated by the inability to achieve an equilibrium solution for a small increase in load.

In accordance with IGE/TD/12 the following factors should be applied to the calculated limited load to demonstrate acceptability:

Design Factor Type 'R' Location	Factor to be Applied to Calculated Limit Load for:	
	Normal Sustained Stress	Abnormal Sustained Stress

[redacted]

0.67	0.80	0.90

3.2 Incremental Plastic Collapse – Elastic Stress Analysis

For the expansion loadcase, the TD/12 criterion states that the linearised primary + secondary membrane and bending stress intensity (Tresca) range must not exceed the lower of,

$$2.0\text{SMYS or } 3.0\left(\frac{\text{UTS}}{2.35}\right) \tag{3}$$

3.2.1 Incremental Plastic Collapse – Elastic-Plastic Stress Analysis

For instances whereby a fitting does not satisfy the above criterion, or unfavourable results are predicted, it may still be possible to qualify the fitting by undertaking an elastic-plastic (non-linear) analysis.

In lieu of a specific criterion in IGE/TD12, the elastic-perfectly-plastic ratcheting assessment criterion of ASME VIII Div 2 [5] Section 5.5.7.2 has been used.

An assessment is performed by application, removal and re application of the loadings. A component is deemed acceptable if any one of the following conditions is met:

1. There is no plastic strain in the component.
2. There is an elastic core in the primary-load-bearing boundary of the component.
3. There is not a permanent change in the overall dimensions of the component.

3.3 Fatigue

From the pipe stress analyses undertaken in Ref. [1,2 &3] two sweepolets failed the IGE/TD/12 fatigue assessment criterion and, as such, are the only fittings considered herein for more detailed assessment.

3.3.1 Sweepolets

In accordance with Appendix 5 of TD/12 the sweepolet body should be assessed using a Class D fatigue curve, defined as:

$$LOG_{10}\,N = 12.2 - 3\,LOG_{10}\,S_R \qquad (for\ N \leq 10^7\ cycles) \tag{4}$$

$$LOG_{10}\,N = 15.6 - 5\,LOG_{10}\,S_R \qquad (for\ N \geq 10^7\ cycles) \tag{5}$$

The header and branch weld should be assessed using a Class F fatigue curve, defined as:

$$LOG_{10}\,N = 11.8 - 3\,LOG_{10}\,S_R \qquad (for\ N \leq 10^7\ cycles) \tag{6}$$

$$LOG_{10}\,N = 15.0 - 5\,LOG_{10}\,S_R \qquad (for\ N \geq 10^7\ cycles) \tag{7}$$

[redacted]

4 RESULTS

4.1 900mm x 900mm Tee

See Appendix A.

4.2 900mm x 90°mm Bend

See Appendix B.

4.3 900mm x 300mm Sweepolet

See Appendix C.

4.4 900mm x 200mm Sweepolet

See Appendix D.

4.5 900mm x 50mm Weldolet

See Appendix E.

4.6 50mm x 50mm Tee

See Appendix F.

[redacted]

5 CONCLUSIONS

1. The 900mm x 900mm tee:
    i. Satisfies the TD/12 global plastic collapse criterion.
    ii. Does not satisfy the local plastic collapse criterion.
        a. A limit load analysis has been performed, for which a limiting load factor of 1.3 was found.
    iii. Does not satisfy the IGE/TD/12 shakedown assessment criterion.
        a. An elastic-plastic ratcheting assessment was performed to the requirements of ASME VIII Division 2. The fitting failed to shakedown to an elastic-plastic load cycle and repeat loadings would eventually lead to incremental plastic collapse.
        b. Shakedown was successfully achieved when considering X65 material grade.
2. The 900mm x 90° bend:
    i. Satisfies the TD/12 limit load analysis criterion.
3. The 900mm x 300mm sweepolet:
    i. Satisfies the TD/12 limit load analysis criterion.
    ii. Satisfies the ASME VIII Division 2 elastic-plastic ratcheting assessment criterion.
    iii. Satisfies the TD/12 fatigue assessment criterion.
4. The 900mm x 200mm sweepolet:
    i. Satisfies the TD/12 limit load analysis criterion.
    ii. Satisfies the ASME VIII Division 2 elastic-plastic ratcheting assessment criterion.
    iii. Satisfies the TD/12 fatigue assessment criterion.
5. The 900mm x 50mm weldolet:
    i. Satisfies the TD/12 limit load analysis criterion.
6. The 50mm x 50mm tee:
    i. Satisfies the TD/12 limit load analysis criterion.

[redacted]

6 RECOMMENDATIONS

Conservative assumptions have been made on the 900mm x 900mm tee material grade and geometry. It is recommended that material scrapings and geometrical measurements of the fitting are undertaken to determine the actual material grade of the fitting and actual fitting wall thicknesses. If the material grade is shown to be higher than X56 and the fitting is shown to be thicker, then a revised model and analysis would be recommended before considering replacing the tee.

7 REFERENCES

1. [redacted]-R0706-21, 'Kings Lynn Compressor Station – Integrity Assessment of Bi-directional Pipework Affected by Ground Subsidence', 13/09/21.
2. [redacted]-R0713-21, 'Kings Lynn Compressor Station – Proposed Removal of Three Pits on Feeder 2 – IGE/TD/12 Stress Analysis, 28/10/21.
3. [redacted]-R0711-21, 'Kings Lynn Compressor Station – IGE/TD/12 Fatigue Analysis of Bi-directional Area Piping', 28/10/21.
4. IGE/TD/12 Edition 2, Reprint with Amendments, Communication 1757, 2012, Pipework Stress Analysis for Gas Industry Plant, Institution of Gas Engineers & Managers.
5. ASME VIII Division 2:2013, 'ASME Boiler & Pressure Vessel Code – Alternative Rules for the Construction of Pressure Vessels', 2013.
6. MSC/PATRAN 2005 r2a, MacNeal-Schwendler Corporation.
7. ABAQUS/Standard Version 6.9.3, Hibbitt, Karlsson & Sorensen Inc., 2009.

8 TABLES

Fitting Type	Assessment Criteria	Reported Code Stress Ratio (%)	Fatigue Usage	Caesar II Model Name	Node Number
900mm x 900mm Tee	Abnormal Sustained	367.09	-	KL_CLAY_SETTLEMENT_FF.C2	6180
	Shakedown	127.13			15220
900mm x 90° Bend	Abnormal Sustained	154.03	-	KL_CLAY_SETTLEMENT_FF.C2	1550
900mm x 300mm Sweepolet	Abnormal Sustained	341.18	-	KL_CLAY_SETTLEMENT_FF_01	6070
	Sustained	112.54	-	KL_FIRM_CLAY_FF_01_PITS_SOFT_FILL	15090
	Shakedown	165.64	-	KL_FIRM_CLAY_FF_01_PITS_SOFT_FILL	15090
	Fatigue	-	1.16	1971_FIRM_CLAY 1998_RF_FIRM_CLAY 1998_FF_FIRM_CLAY 2003-2021_RF_FIRM_CLAY 2003-2021_FF_FIRM_CLAY 2021-2050_X10_RF_FIRM_CLAY_NO_PITS_SOFT_FILL 2021-2050_X10_FF_FIRM_CLAY_NO_PITS_SOFT_FILL	6070
900mm x 200mm Sweepolet	Abnormal Sustained	255.31	-	KL_CLAY_SETTLEMENT_FF_01	1310
	Sustained	111.84	-	KL_FIRM_CLAY_FF_01_PITS_SOFT_FILL	15990
	Shakedown	164.47	-	KL_CLAY_SETTLEMENT_RF_01	15990
	Fatigue	-	14.18	1971_FIRM_CLAY 1998_RF_FIRM_CLAY 1998_FF_FIRM_CLAY 2003-2021_RF_FIRM_CLAY 2003-2021_FF_FIRM_CLAY 2021-2050_X10_RF_FIRM_CLAY_NO_PITS_SOFT_FILL 2021-2050_X10_FF_FIRM_CLAY_NO_PITS_SOFT_FILL	15990
900mm x 50mm Weldolet	Abnormal Sustained	105.97	-	KL_CLAY_SETTLEMENT_FF_01	6160

[redacted]

50mm x 50mm Tee	Abnormal Sustained	141.84	-	KL_CLAY_SETTLEMENT_FF_01	16980

Table 1 – Fitting Type and Loadcases Considered for FEA

[redacted]

APPENDIX A 900MM X 900MM TEE ASSESSMENT

A.1 GEOMETRY

In the absence of specific geometrical data the geometry of the tee is assumed to satisfy the criteria given in IGE/TD/12 and the minimum wall thickness requirements of the 1972 edition of T1. The dimensions used are shown in Table A1 and Figure A1.

A.2 FINITE ELEMENT MODEL

A three-dimensional finite element (FE) model of the tee was constructed using MSC Patran [6] and analysed using the general purpose FE code ABAQUS [7]. Twenty-noded, three degree of freedom reduced integration brick (hexahedral) elements, C3D20R, were used for the analysis.

Beam elements representing the pipe stress model are tied to the open ends of the 3D solid model using rigid multi-point constraints (MPCs), as shown schematically in Figure A1. The three nodes J(1), J(2) and J(3) are coincident at the intersection but are not connected. The branch node, J(3), is fixed by a translational and rotational boundary condition, whilst forces and moments are applied at the header nodes J(1) and J(2).

The beams allow the application of forces and moments from the pipe stress model onto the solid model of the fitting. Adequate lengths of header and branch pipe are modelled such that the local effects of the MPCs are removed from the area of interest at the fitting.

The FE mesh created for the 900mmx900mm tee is shown in Figure A2.

A.3 MATERIAL PROPERTIES

Young's modulus and Poisson's ratio equal to 210000 N/mm^2 and 0.3, respectively, were used in all analyses. The material grade of the tee is unknown and has therefore been modelled assuming minimum required mechanical properties as per T1. A material grade of X56 has been assumed which has a SMYS of 386MPa and SMUTS of 489MPa. The matching header and branch piping is API-5l X60 which has a SMYS of 413MPa and a SMUTS of 517MPa.

A.4 LOADS

A.4.1 **Internal Pressure**

Distributed pressure loads were applied to all internal surfaces.

In order to represent the branch and one of the header sections being 'capped off' downstream of the fitting, pressure end loads were applied to the header pipe elements via the MPCs. The branch pressure end load was taken into consideration by the reaction at the branch boundary condition.

[redacted]

A.4.2 **System Forces and Moments**

For each of the assessment criteria considered, forces and moments were extracted for the most highly stressed fitting only, details of the IGE/TD/12 assessments considered and associated loadcase from the pipe stress analysis are provided in Table A2.

Before application to the FE model, the extracted forces and moments were converted to the axis convention of the FE model.

The extracted forces and moments are given in Table A3 and Table A4 and the forces and moments applied to the FE model are given in Table A5 and Table A6.

A.5 ANALYSIS

Linear elastic analyses of the finite element model are initially performed to determine the stresses in the fitting. The stresses are then compared to the allowable stress criteria for the various failure modes for the acceptability.

The following failure modes are checked;

- Plastic collapse
  - Global plastic collapse
  - Local plastic collapse
- Shakedown

Where the linear elastic stress results exceed the allowable stress limits, elastic-plastic (non-linear) stress analysis is performed to determine the acceptability of the fitting.

A.6 RESULTS

A.6.1 **Internal Pressure**

A contour plot of maximum principal stresses due to an internal pressure loading of 79.5 barg (MIP) is presented in Figure A3. Away from concentrations, maximum principal stress in the adjoining pipe is in the range 200 to 230 MPa. Classical theory predicts a hoop stress of 228.6 MPa in the outside wall for a wall thickness of 15.9 mm. This provides some confidence in the model.

A.6.2 **Plastic Collapse (Sustained)**

A.6.2.1 **Global Primary Membrane Stress**

Figure A4 shows the stress intensity (Tresca) stress on the tee for the abnormal sustained (including settlement) loadcase.

Taking SCLs at appropriate locations away from discontinuities and concentrations, from Table A7 it is shown that the general primary membrane stress, P_m, is less than the allowable stress limit prescribed in TD/12.

[redacted]

A.6.2.2 **Local Primary Membrane Stress Plus Primary Bending**

Taking SCLs at appropriate locations to include discontinuities, but not concentrations, from Table A7, it is shown that the local primary membrane stress plus primary bending stress, $P_L + P_b$, is greater than the allowable stress limit prescribed in TD/12.

A.6.2.3 **Limit Load Analysis**

The linear elastic stress analysis showed an unacceptable stress margin for the local plastic collapse criteria. A limit load analysis has therefore been performed in accordance with Section A6.7 of TD/12.

Table A8 summarises the results of the assessment, a limiting load factor of 1.30 was found for the abnormal sustained loadcase, and therefore the tee is fit for purpose for the anticipated abnormal sustained (including settlement) loadings.

A.6.3 **Shakedown**

Figure A6 shows the Tresca stress range for the shakedown loadcase L9. Considering the mostly highly stressed region (adjacent the crotch), Table A9 shows the maximum linearised Tresca stress range exceeds the code allowable value.

A.6.3.4 **Shakedown - Elastic-Plastic Assessment**

The linear elastic stress analysis showed an unacceptable stress margin for the local plastic collapse criterion. In lieu of a more accurate approach to consider shakedown loads within IGE/TD/12, an elastic-perfectly-plastic (non-linear) analysis has been performed in accordance with ASME VIII Division 2 and the results are provided in Figure A7.

The strain at the most highly stressed region, located at the tee crotch, has been considered for assessment. From Figure A7, it is shown that the plastic equivalent strain (peeq) at this location under repeated cyclic loadings continues to increase (ratchet). The implication is that plastic strain could increase under repeated cyclic loading and eventually cause failure of the fitting.

It should be borne in mind that specified minimum mechanical material grade (X56) and geometrical properties (minimum taken from T1 1972) have been considered for the assessment and it may be possible to demonstrate acceptability of the fitting with measured material and geometrical properties.

It is recommended that material scrapings and geometrical measurements of the fitting are undertaken to determine the actual material grade of the fitting and actual fitting wall thicknesses. If the material grade is shown to be higher than X56 and the fitting is shown to be thicker, then a revised model and analysis would be recommended before considering replacing the tee.

[redacted]

A.7 CONCLUSIONS

1. A three-dimensional finite element model of the 900mmx900mm tee has been created.

2. System forces and moments, giving rise to the abnormal sustained and shakedown exceptions, have been extracted from the relevant pipe stress model and applied on the FE model together with internal pressure.

3. Finite element analysis of the 900mmx900mm tee has been undertaken using the ABAQUS software, with a subsequent design-by-analysis (DBA) assessment to the TD/12 DBA criterion for abnormal sustained and shakedown loadcases only.

4. The Tresca stress in the 900mmx900mm tee have been shown to be less than the TD/12 DBA criteria for global plastic collapse.

5. The Tresca stress in the 900mmx900mm tee have been shown to exceed the TD/12 DBA criteria for local plastic collapse, for the abnormal sustained loadcase.

    a. A subsequent limit load analysis has been undertaken which demonstrates that the predicted collapse pressure exceeds the maximum incidental pressure of 79.5 barg.

6. The Tresca stress range in the 900mmx900mm tee exceeds the TD/12 DBA criteria for incremental plastic collapse (shakedown).

    a. A subsequent elastic-perfectly plastic analysis to the requirements of ASME VIII Div II shows that shakedown is not achieved. The implication is that the plastic strain could increase under repeated cyclic loading and eventually cause failure of the fitting.

A.8 RECOMMENDATIONS

Conservative assumptions have been made on the 900mm x 900mm tee material grade and geometry. It is recommended that material scrapings and geometrical measurements of the fitting are undertaken to determine the actual material grade of the fitting and actual fitting wall thicknesses. If the material grade is shown to be higher than X56 and the fitting is shown to be thicker, then a revised model and analysis would be recommended before considering replacing the tee.

[redacted]

Matching Pipe			Tee						
Diameter	Wall Thickness	Material Grade	Header Diameter	Branch Diameter	Header Wall Thickness	Branch Wall Thickness	Crotch Radius	Material Grade X56	
								SMYS	UTS
914.4	15.9	X65	945.2	31.3	31.3	945.2	50	386	489

Table A1 – 900mm x 900mm Tee Details

Assessment Criteria	Reported Code Stress Ratio (%)	Model Name	Node Number
Abnormal Sustained	367.09	KL_CLAY_SETTLEMENT_FF.C2	6180
Shakedown	127.13		15220

Table A2 – Loadcases Assessed

[redacted]

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
6175	-3212	-203787	-260149	2051211	30853	-94889
6180	3212	203787	260149	-2187248	-28694	94878
6180	-6508	-153716	-274042	1516618	49697	130123
6190	6508	153716	274042	-1619111	-45316	-130146
6180	1278	-50615	9834	670630	-21003	-225001
9730	-1278	50615	-9834	-670543	27621	259054

Table A3 – Loadcase 6, Occasional, Extracted Forces and Moments, 900mmx900mm Tee, Node 6180

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
6175	-106331	-4368	- 1188629	-11020	-679148	-3729
6180	106331	4368	1188629	12389	750709	3344
6180	-10173	-9200	-911197	-18744	68099	11163
6190	10173	9200	911197	15856	-61253	-11200
6180	94349	-4828	277526	-6355	725420	12882
9730	-94349	4828	-277526	6355	-818808	-14507

Table A4 – Loadcase 9, Shakedown, Extracted Forces and Moments, 900mmx900mm Tee, Node 6180

ABAQUS Node	Load Type	Value
316204	FX (N)	260149
	FY (N)	3212
	FZ (N)	-203787
	MX (N.mm)	94878000
	MY (N.mm)	-2187248000
	MZ (N.mm)	28694000
316205	FX (N)	-274042
	FY (N)	-6508
	FZ (N)	153716
	MX (N.mm)	130123000
	MY (N.mm)	1516618000
	MZ (N.mm)	-49697000

Table A5 – ABAQUS Input, Loadcase L6

ABAQUS Node	Load Type	Value

316204	FX (N)	1188629
	FY (N)	106331
	FZ (N)	-4368
	MX (N.mm)	3344000
	MY (N.mm)	12389000
	MZ (N.mm)	-7.5E+08
316205	FX (N)	-911197
	FY (N)	-10173
	FZ (N)	9200
	MX (N.mm)	11163000
	MY (N.mm)	-1.9E+07
	MZ (N.mm)	-6.8E+07

Table A6 – ABAQUS Input, Loadcase L9

Region	Primary Membrane Stress, P_m (MPa)	Allowable Stress (MPa) (f)	Margin on Global Plastic Collapse	Primary Local Membrane, P_L (MPa)	Primary Bending, P_b (MPa)	$P_L + P_b$	Allowable Stress (MPa) (1.5f)	Margin on Local Plastic Collapse
Branch	186.35	332.50	1.78	339.60	222.40	562.00	498.75	0.89
Branch 90°	88.17	332.50	3.77	184.00	520.90	704.90	498.75	0.74
Header	144.40	332.50	2.30	339.60	215.40	555.00	498.75	0.94
Crotch	186.35	332.50	1.78	581.20	222.40	803.60	498.75	0.65
Flank	259.40	332.50	1.28	459.30	220.70	680.00	498.75	0.77

Table A7 – Abnormal Sustained Results

	Abnormal Sustained Loadcase
Loading Factor at Instability	1.44
TD/12 Factor	0.9
Limiting Loading Factor	1.30

Table A8 – Limit Load Assessment

Loadcase	Local Membrane + Bending Stress (MPa)	Allowable Stress (3S) (MPa)	Margin on Local Plastic Collapse
L9	978.26	624.26	**0.64**

Table A9 – Shakedown - ASME VIII Division 2, Incremental Plastic Collapse (Ratchetting) Results

[redacted]

A.9 FIGURES

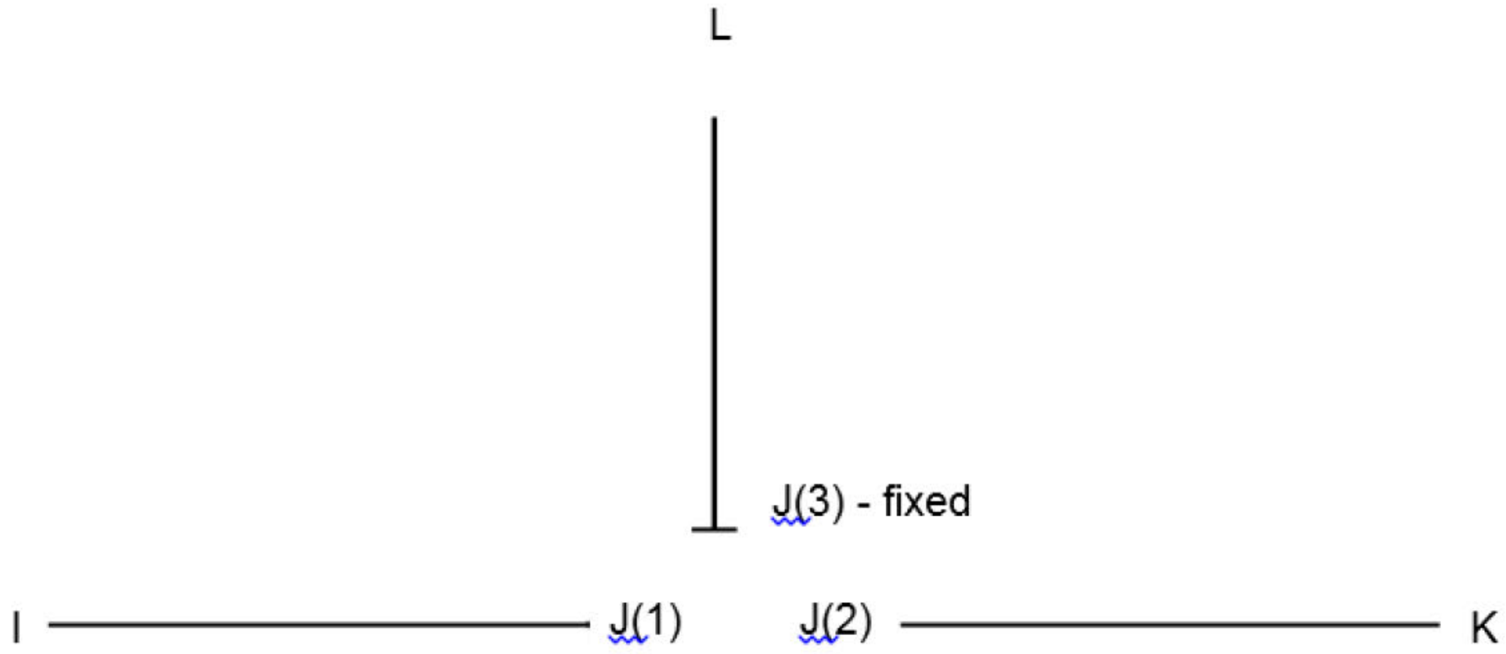


Figure A1 - Model Schematic

[redacted]

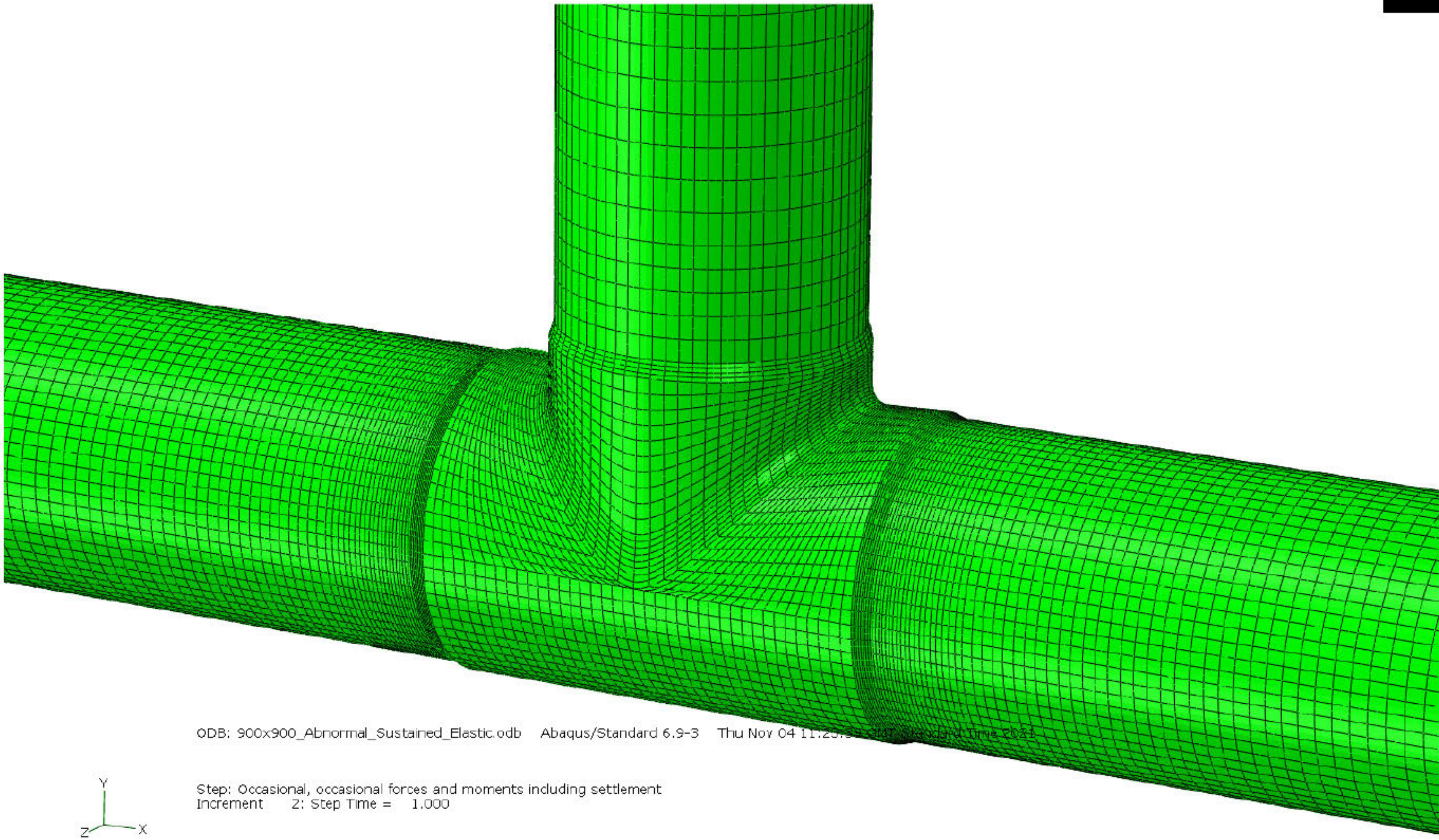


Figure A2 – Finite Element Mesh

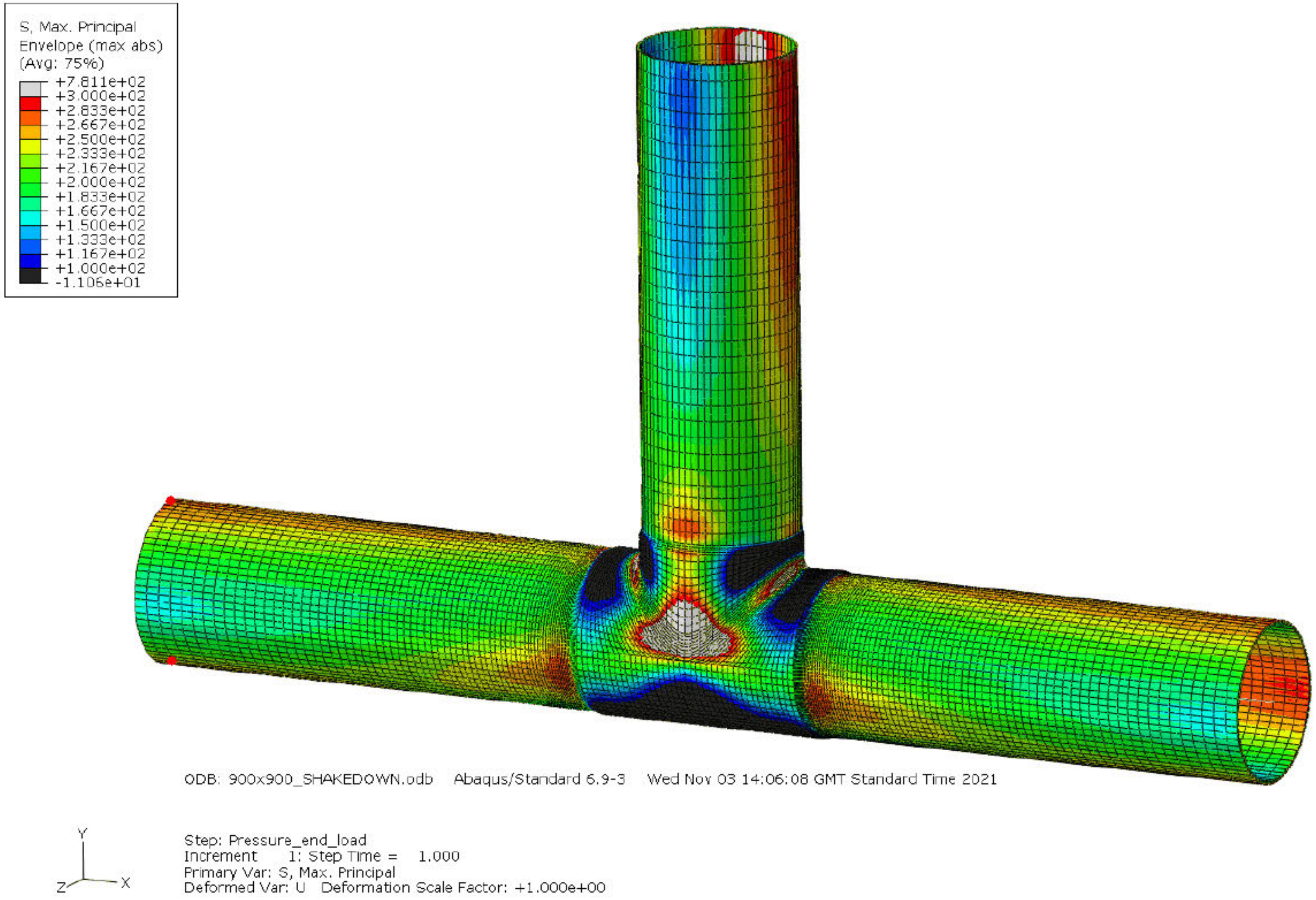
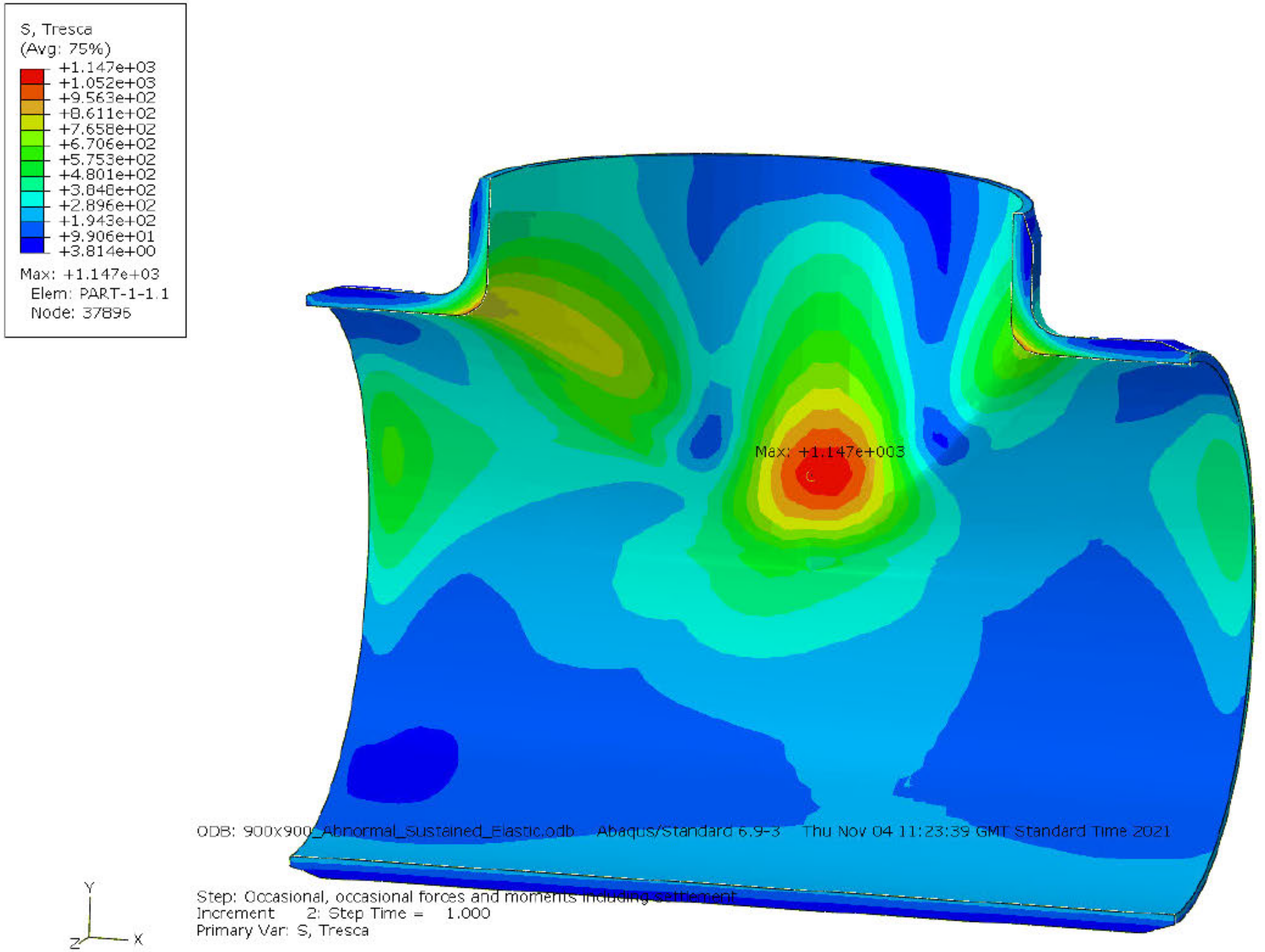


Figure A3 – Max. Principal Stress – Pressure

[redacted]



<u>**Figure A4 – Tresca Equivalent Stress – Abnormal Sustained Loadcase – Elastic**</u>

[redacted]

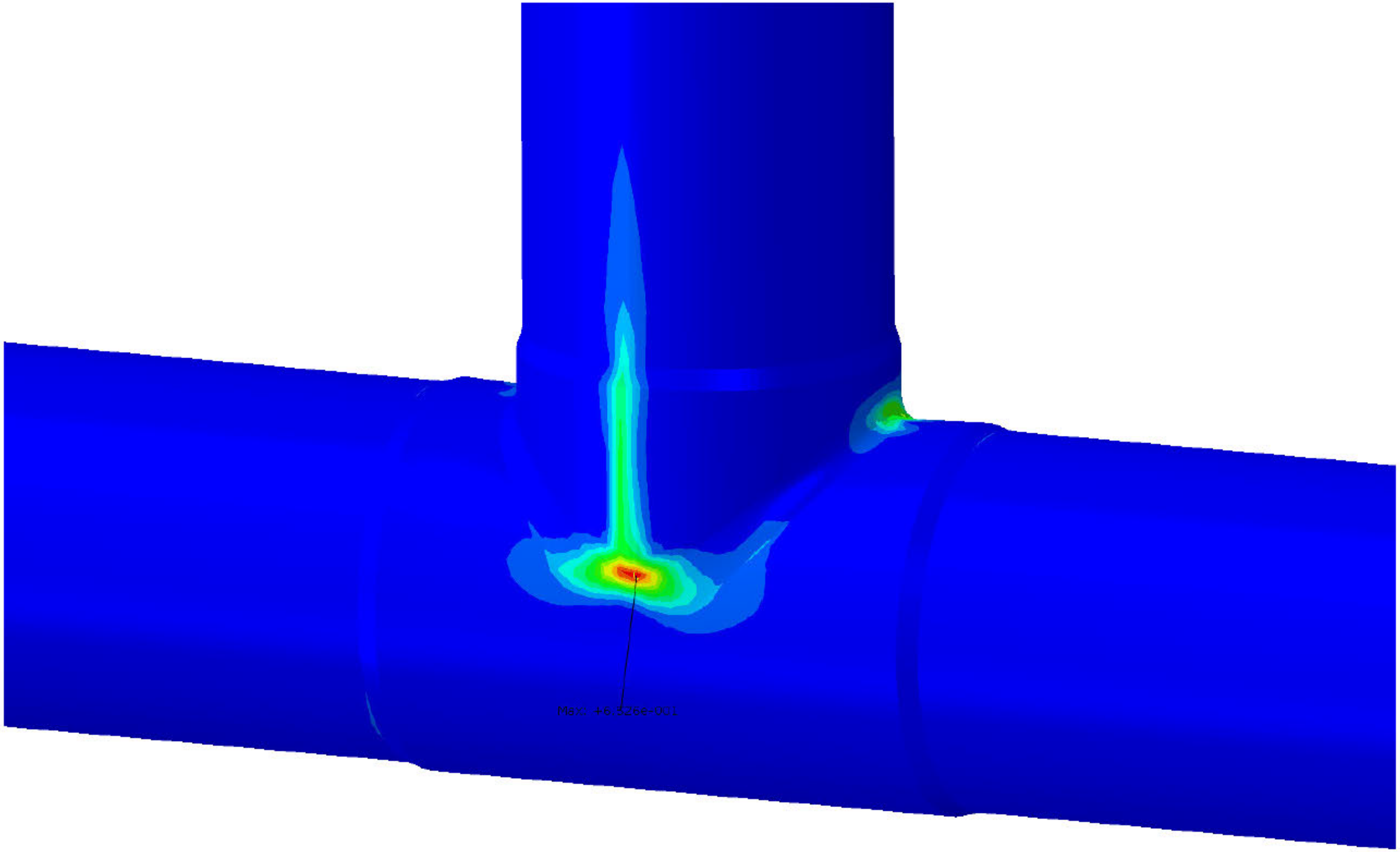


Figure A5 – Location of Max. PEEQ, for Limit Load Analysis – Abnormal Sustained

[redacted]

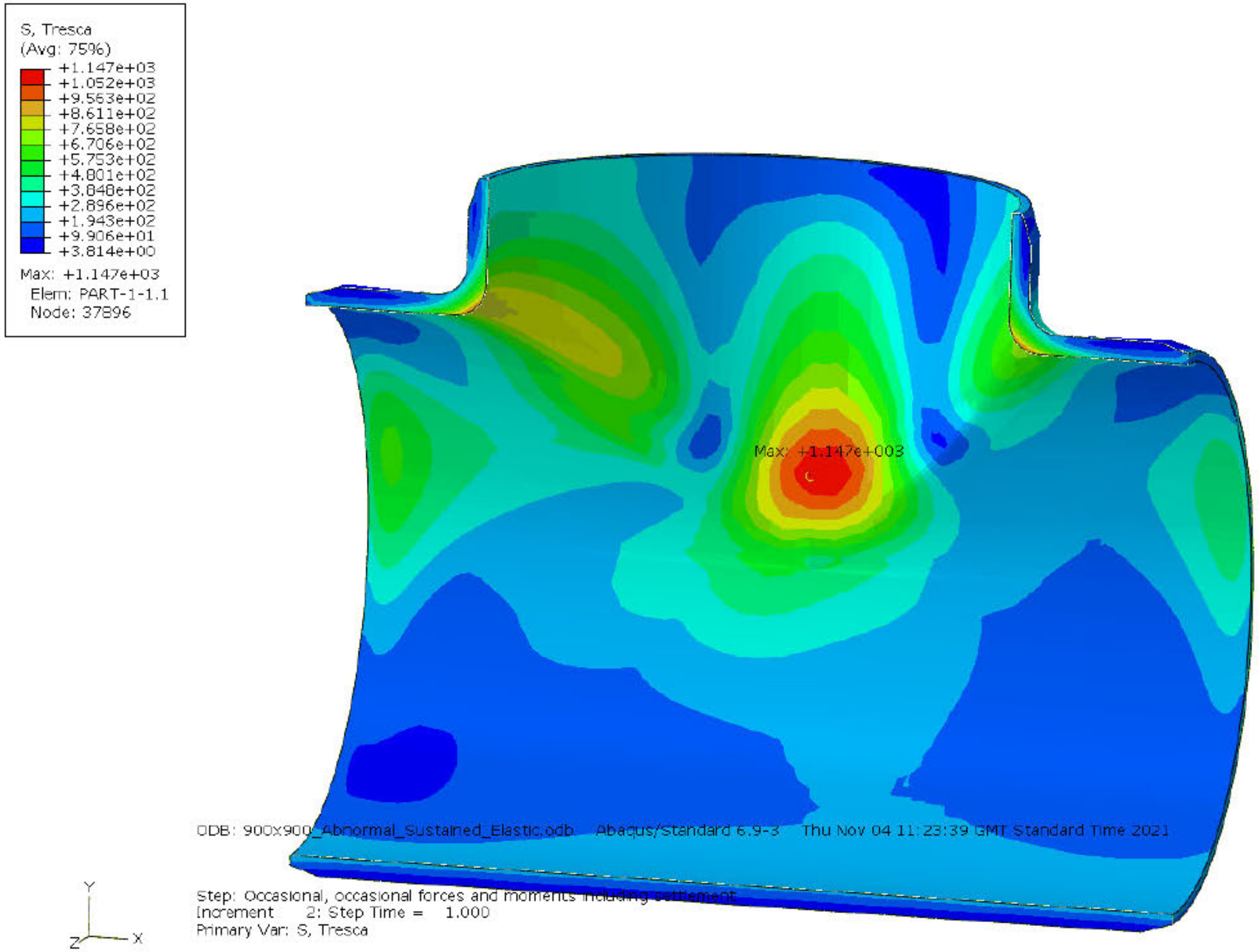
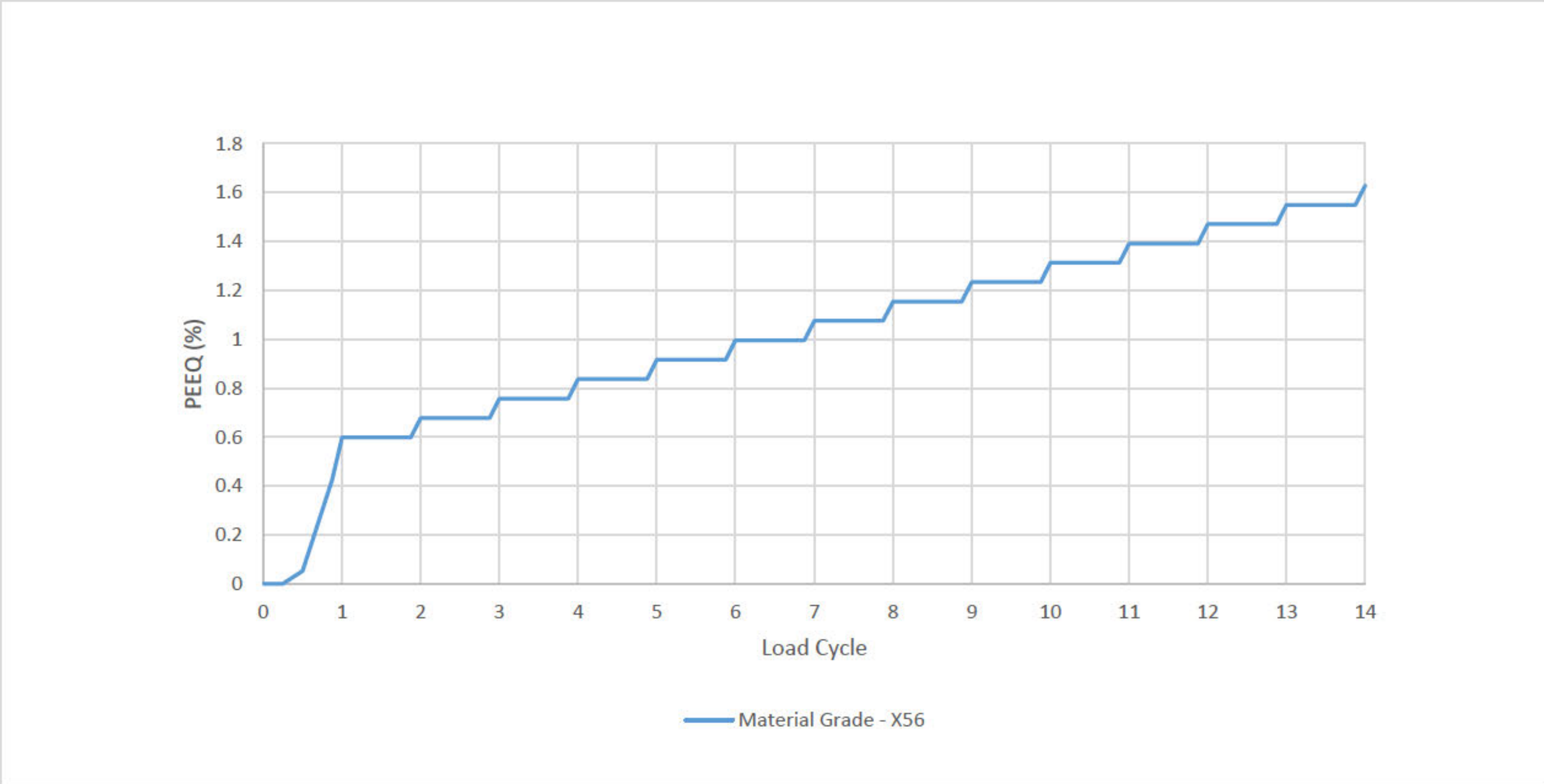


Figure A6 – Tresca Stress Range - Loadcase 9 – Shakedown Loadcase – Elastic



<u>Figure A7 – Equivalent Plastic Strain (PEEQ) - Loadcase 9 – ASME VIII Incremental Plastic Collapse Assessment</u>

APPENDIX B 900MM X 90° BEND ASSESSMENT

B.1 GEOMETRY

In the absence of specific geometrical data the geometry of the bend is assumed to satisfy the criteria given in IGE/TD/12 and the minimum specified wall thickness and material properties of the 1973 edition of B1. The dimensions used are shown in Table B1.

B.2 FINITE ELEMENT MODEL

The three-dimensional finite element (FE) model of the bend was constructed using MSC Patran and analysed using the general purpose FE code ABAQUS. Twenty-noded, three degree of freedom reduced integration brick (hexahedral) elements, C3D20R, were used for the analysis.

Beam elements representing the pipe stress model are tied to the open ends of the 3D solid model using rigid multi-point constraints (MPCs), as shown schematically in Figure B1. The three nodes J(1), J(2) and J(3) are coincident at the intersection but are not connected. The branch node, J(3), is fixed by a translational and rotational boundary condition, whilst forces and moments are applied at the header nodes J(1) and J(2).

The beams allow the application of forces and moments from the pipe stress model onto the solid model of the fitting. Adequate lengths of pipe are modelled such that the local effects of the MPCs are removed from the area of interest at the fitting.

The FE mesh created for the 900mmx90° bend is shown in Figure B2.

B.3 MATERIAL PROPERTIES

Young's modulus and Poisson's ratio equal to 210000 N/mm^2 and 0.3, respectively, were used in all analyses. The material grade of the tee is unknown and has therefore been modelled assuming minimum required mechanical properties as per T1. The bend and matching pipe is material grade X65 which has a SMYS of 448MPa and SMUTS of 530MPa.

B.4 LOADS

B.4.1 Internal Pressure

Distributed pressure loads were applied to all internal surfaces.

In order to represent the bend being 'capped off' downstream of the fitting, a pressure end loads is applied to End1 via the MPC. The pressure end load at End2 is taken into consideration by the reaction at the other MPC.

B.4.2 Applied Displacements

[redacted]

Large vertical displacements, due to settlement, were predicted from the pipe stress analysis, and therefore a strain based analysis has been undertaken of the bend, whereby boundary displacements/rotations, and not loads, are applied to the model.

For the assessment criterion considered (sustained loading), displacements and rotations were extracted for the most highly stressed fitting only, details of the IGE/TD/12 assessment considered and associated loadcase from the pipe stress analysis are provided in Table B2.

The applied displacements and rotations are given in Table B3.

B.5 ANALYSIS

The assessment of the 900mmx900mm tee, of Appendix A, indicated very high stresses in the fitting which exceeded the linear elastic assessment criteria of IGE/TD/12, for both plastic collapse and shakedown.

For this reason, and in order to obtain a more accurate solution, a non-linear analysis has been undertaken to determine the acceptability of the 900mmx90° bend.

B.5.1 **Plastic Collapse (Limit Load Analysis)**

Protection against plastic collapse is demonstrated by undertaking an elastic-perfectly-plastic (limit load) analysis to determine the load which causes overall structural instability.

B.6 RESULTS

B.6.1 **Internal Pressure**

A contour plot of maximum principal stresses due to an internal pressure loading of 79.5 barg is presented in Figure B3. Away from concentrations, maximum principal stress in the adjoining pipe is in the range 200 to 230 MPa. Classical theory predicts a hoop stress of 228.6 MPa in the outside wall for a wall thickness of 15.9 mm. This provides some confidence in the model.

B.6.2 **Abnormal Sustained**

Table B4 summarises the results of the limit load assessment. A limiting load factor of 2.07 was found, and therefore the bend is fit for purpose for the anticipated abnormal sustained loadings (including settlement).

B.7 TABLES

Matching Pipe			Bend		
Diameter	Wall Thickness	Material Grade	Wall Thickness (mm)	Material Grade	
				X65	
				SMYS	UTS
914.4	15.9	X65	19.9	448	530

Table B1 – 900mm x 90° Bend Details

Assessment Criteria	Reported Code Stress Ratio (%)	Model Name	Node Number
Abnormal Sustained	154.03	KL_CLAY_SETTLEMENT_FF.C2	1550

Table B2 – Loadcases Assessed

Node	DX mm.	DY mm.	DZ mm.	RX radians	RY radians	RZ radians
1535	-2.137	-99.223	1.796	0.0180	-0.0007	0.0012
2691	-3.209	-138.172	2.423	0.0134	-0.0001	0.0116

Table B3 – Loadcase 6, Occasional, Extracted Displacements, 900mmx90° Bend, Node 1535 and 2691

	Abnormal Sustained Loadcase
Loading Factor at Instability	2.3
TD/12 Factor	0.9
Limiting Loading Factor	2.07

Table B4 – Limit Load Assessment

[redacted]

B.8 FIGURES

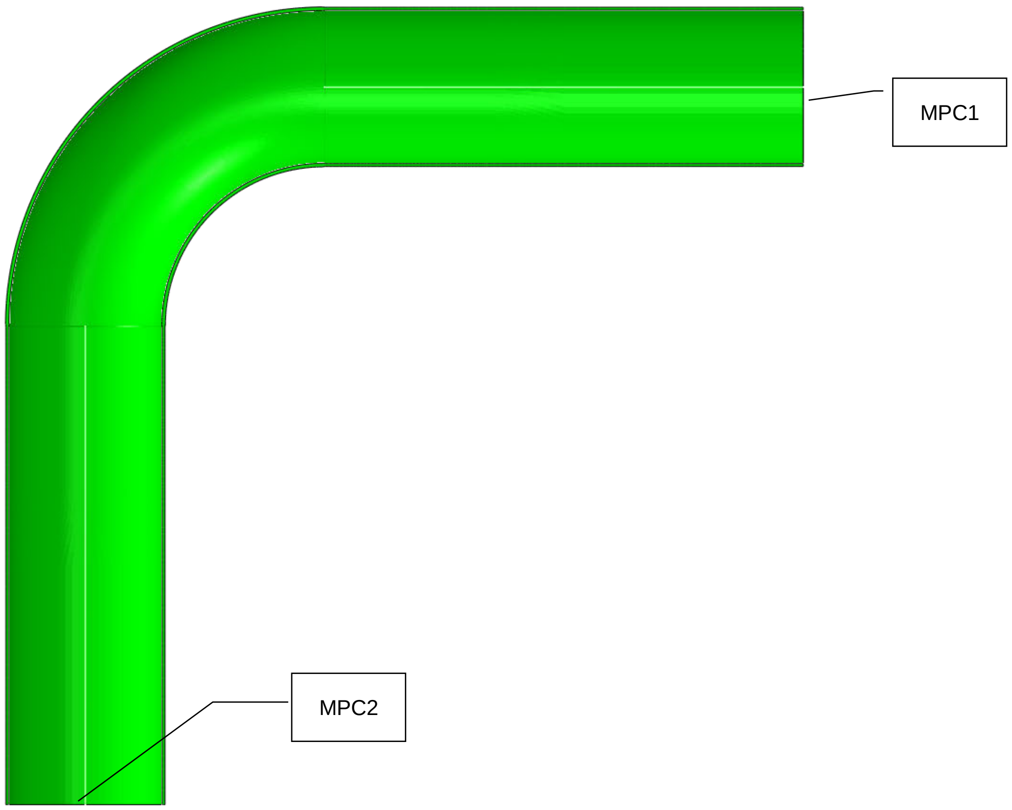


Figure B1 – 900mm x 90°Bend - Model Schematic

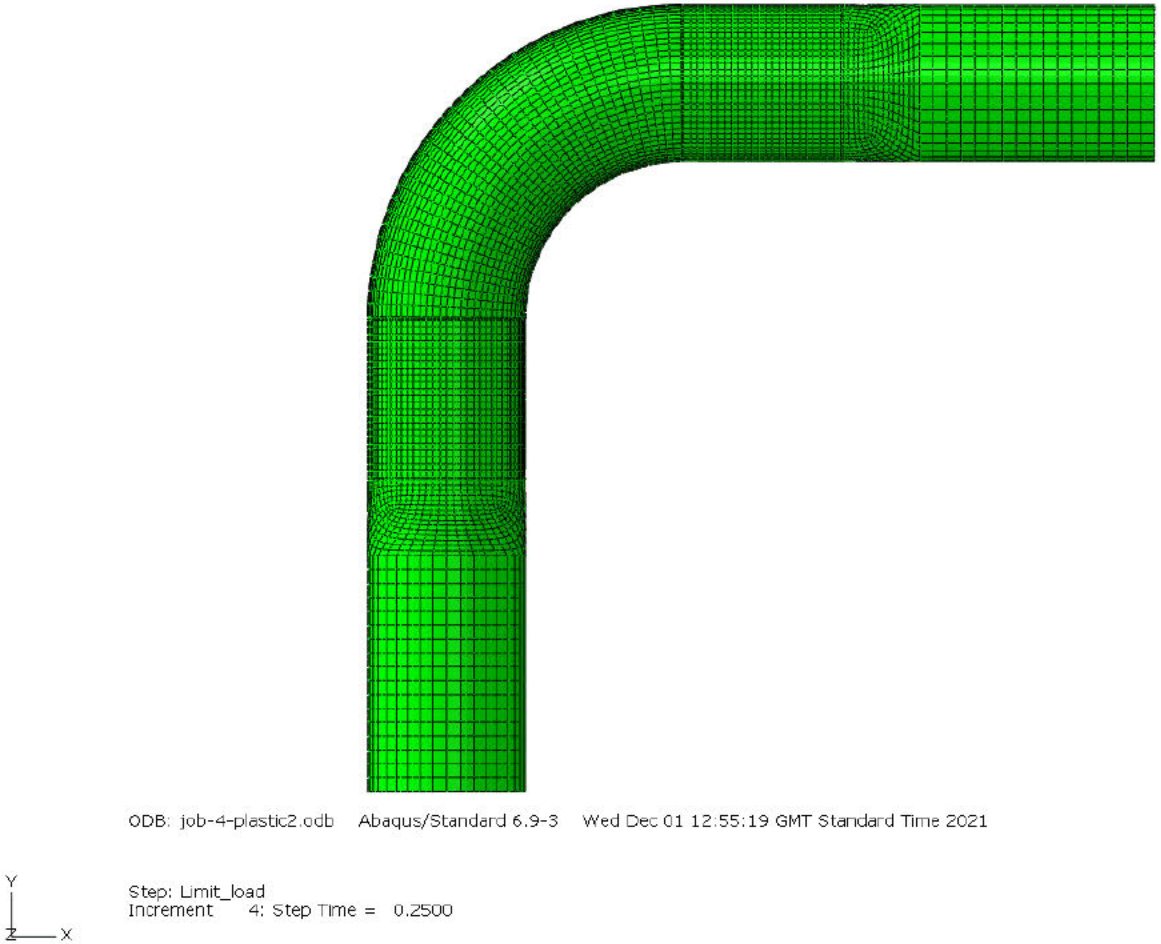
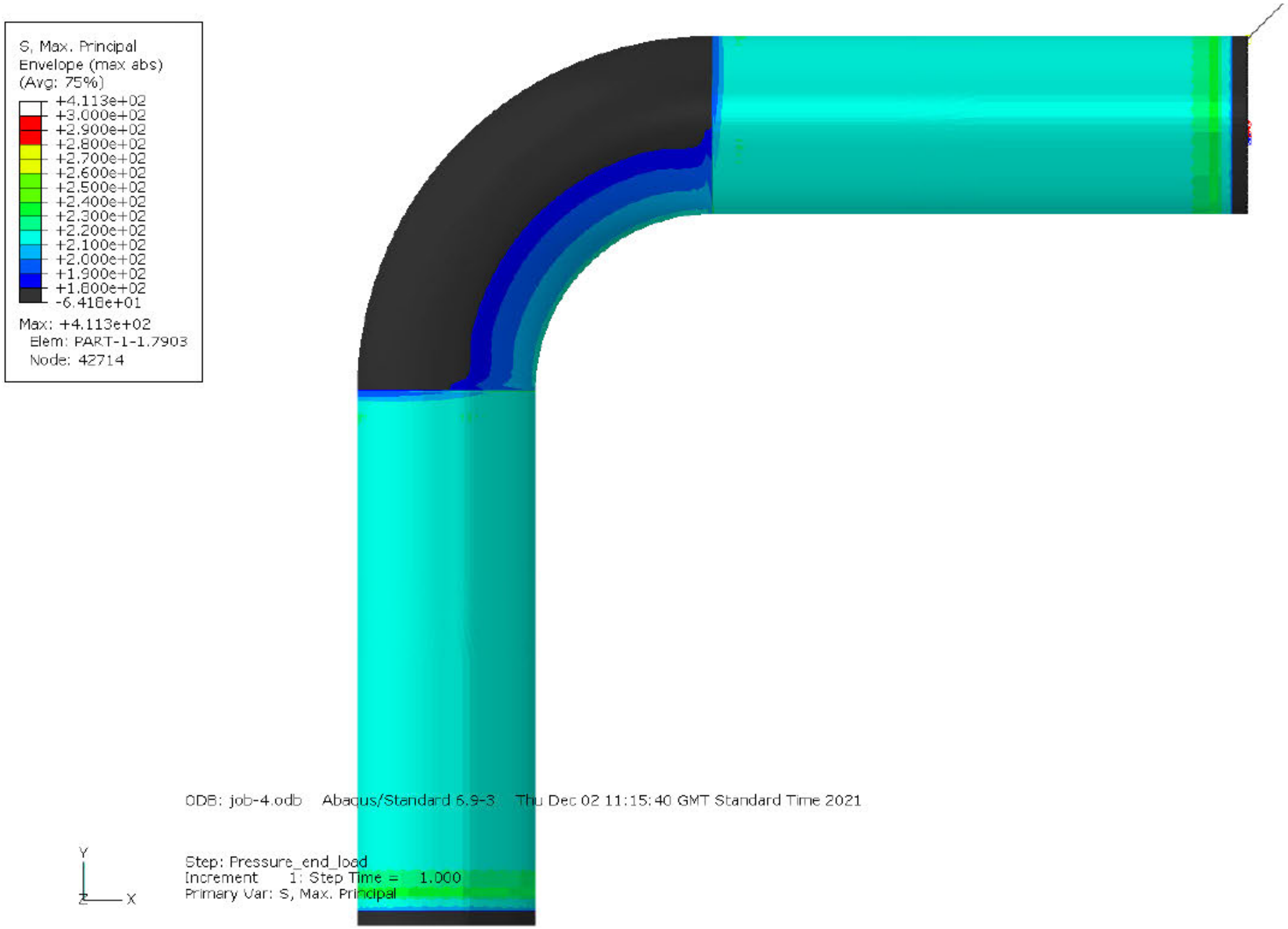


Figure B2 – 900mm x 90° Bend - Mesh

[redacted]



<u>Figure B3 – 900mm x 90° Bend – Maximum Principal Stress – Pressure Only</u>

[redacted]

B.9 CONCLUSIONS

1. A three-dimensional finite element model of the 900mmx90° bend has been created.

2. Displacements and rotations, giving rise to the abnormal sustained exception, have been extracted from the relevant pipe stress model and applied on the FE model together with internal pressure.

3. Finite element analysis of the 900mmx90° bend has been undertaken using the ABAQUS software, with a subsequent limit load analysis assessment to the TD/12 criterion for abnormal sustained loading only.

4. A limiting load factor of 2.07 was found, and therefore the bend is fit for purpose for the anticipated abnormal sustained loadings (including settlement).

[redacted]

APPENDIX C 900MM X 300MM SWEEPOLET ASSESSMENT

C.1 GEOMETRY

In the absence of specific geometrical data the geometry of the sweepolet is assumed to meet the requirements of the 1971 edition of F1. The dimensions used are shown in Figure C1.

C.2 FINITE ELEMENT MODEL

The three-dimensional finite element (FE) model of the sweepolet was constructed using MSC Patran and analysed using the general purpose FE code ABAQUS. Twenty-noded, three degree of freedom reduced integration brick (hexahedral) elements, C3D20R, were used for the analysis.

Beam elements representing the pipe stress model are tied to the open ends of the 3D solid model using rigid multi-point constraints (MPCs), as shown schematically in Figure C2. The three nodes J(1), J(2) and J(3) are coincident at the intersection but are not connected. The branch node, J(3), is fixed by a translational and rotational boundary condition, whilst forces and moments are applied at the header nodes J(1) and J(2).

The beams allow the application of forces and moments from the pipe stress model onto the solid model of the fitting. Adequate lengths of header and branch pipe are modelled such that the local effects of the MPCs are removed from the area of interest at the fitting.

The FE mesh created for the 900mmx300mm sweepolet is shown in Figure C3.

C.3 MATERIAL PROPERTIES

Young's modulus and Poisson's ratio equal to 210000 N/mm^2 and 0.3, respectively, were used in all analyses. The material grade of the sweepolet is unknown and has therefore been modelled assuming minimum required mechanical properties as per F1 1972. A material grade of X60 has been assumed which has a SMYS of 413MPa and SMUTS of 517MPa.

Material property details for the sweepolet and matching header and branch are provided in Table C1.

C.4 LOADS

C.4.1 **Internal Pressure**

Distributed pressure loads were applied to all internal surfaces.

In order to represent the branch and one of the header sections being 'capped off' downstream of the fitting, pressure end loads were applied to the header pipe elements via the MPCs. The branch pressure end load was taken into consideration by the reaction at the branch boundary condition.

[redacted]

C.4.2 **System Forces and Moments**

For each of the assessment criteria considered, forces and moments were extracted for the most highly stressed fitting only, details of the IGE/TD/12 assessments considered and associated loadcase from the pipe stress analysis are provided in Table C2.

Before application to the FE model, the extracted forces and moments were converted to the axis convention of the FE model.

The extracted forces and moments are provided in Table C3 to Table C6 and the forces and moments applied to the FE model are given in Table C7 to Table C10.

C.5 ANALYSIS

The assessment of the 900mmx900mm tee, of Appendix A, indicated very high stresses in the fitting which exceeded the linear elastic assessment criteria of IGE/TD/12, for both plastic collapse and shakedown. For this reason, and in order to obtain a more accurate solution, non-linear analyses have been undertaken to determine the acceptability of the 900mmx300mm sweepolet.

C.5.1 **Plastic Collapse (Limit Load Analysis)**

Protection against plastic collapse is demonstrated by undertaking an elastic-perfectly-plastic (limit load) analysis to determine the load which causes overall structural instability.

C.5.2 **Shakedown (Incremental Plastic Collapse)**

IGE/TD/12 does not provided guidance for undertaking a non-linear analysis to consider shakedown loads, therefore an elastic-perfectly-plastic analysis has been performed in accordance with ASME VIII Division 2. Details of the assessment are provided in Section 3.2.1.

C.6 RESULTS

C.6.1 **Internal Pressure**

A contour plot of maximum principal stress due to an internal pressure loading of 79.5 barg is presented in Figure C4. Away from concentrations, maximum principal stress in the adjoining pipe is in the range 200 to 230 MPa. Classical theory predicts a hoop stress of 228.6 MPa in the outside wall for a wall thickness of 15.9 mm. This provides some confidence in the model.

C.6.1.5 **Sustained**

Table C11 summarises the results of the assessments, limiting loading factors of 1.52 and 1.33 were found for the abnormal and normal sustained loadcases, and therefore the sweepolet is fit for purpose for the anticipated sustained loadings.

[redacted]

C.6.2 **Shakedown**

Only the most highly stressed region, located at the sweepolet crotch, has been considered for assessment. From Figure C5, it is shown that for an assumed minimum material grade of X60 shakedown is successfully achieved.

Figure C6 shows the maximum predicted displacement of the fitting for thirteen repeat load cycles. It is shown that the predicted displacement does not change significantly from the first to last load cycle. It can thus be inferred that the overall dimensions of the fitting have not changed and the tee satisfies the ASME VIII elastic-plastic ratcheting criteria.

C.6.3 **Fatigue**

Table C12 shows the results of the fatigue assessment, the maximum past + future cumulative usage was calculated to be 0.43 at the sweepolet crotch, and therefore the sweepolet is considered to be fit for purpose for the past and anticipated future fatigue duties.

[redacted]

C.7 CONCLUSIONS

1. A three-dimensional finite element model of the 900mmx300mm sweepolet has been created.

2. System forces and moments, giving rise to the sustained, shakedown and fatigue exceptions have been extracted from the relevant pipe stress model and applied on the FE model together with internal pressure.

3. Finite element analysis of the 900mmx300mm sweepolet has been undertaken using the ABAQUS software, with a subsequent limit load and fatigue assessment to the TD/12 DBA criterion for sustained and fatigue loadcases only.

4. In lieu of a TD/12 elastic-plastic shakedown criterion, an incremental plastic collapse assessment has been undertaken to the requirements of ASME VIII Division 2.

5. Limiting loading factors of 1.57 and 1.46 were found for the normal and abnormal sustained loadcases, and therefore the sweepolet is fit for purpose for the anticipated sustained loadings.

6. The 900mmx300mm sweepolet has been shown to satisfy the elastic-plastic incremental plastic collapse criterion of ASME VIII Div 2.

7. The 900mmx300mm sweepolet has been shown to satisfy the DBA fatigue criterion of TD/12.

[redacted]

Matching Pipe								Sweepolet		
Header				Branch						
Diameter	Wall Thickness	Material Grade		Diameter	Wall Thickness	Material Grade		Dimensions	Material Grade	
		X60				X46			X60	
		SMYS	UTS			SMYS	UTS		SMYS	UTS
914.4	15.9	413	517	219.1	8.2	317	434	**See Figure C1**	413	517

Table C1 – 900mm x 300mm Sweepolet Details

Assessment	Reported Code Stress Ratio (%)	Usage	Model Name	Node Number
Abnormal Sustained	341.18	-	KL_CLAY_SETTLEMENT_FF_01	6070
Sustained	112.54	-	KL_FIRM_CLAY_FF_01_PITS_SOFT_FILL	15090
Shakedown	165.64	-	KL_FIRM_CLAY_FF_01_PITS_SOFT_FILL	15090
Fatigue	-	1.16	1971_FIRM_CLAY 1998_RF_FIRM_CLAY 1998_FF_FIRM_CLAY 2003-2021_RF_FIRM_CLAY 2003-2021_FF_FIRM_CLAY 2021-2050_X10_RF_FIRM_CLAY_NO_PITS_SOFT_FILL 2021-2050_X10_FF_FIRM_CLAY_NO_PITS_SOFT_FILL	6070

Table C2 – Loadcases Assessed

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
6069	-411	9950	-3296	-18180	-4172	-7268
6070	411	-9950	3296	18180	5062	9954
6150	437	-380703	-244247	1746167	36785	-85405
6070	-437	380703	244247	-1765248	-36807	85405
6070	-401	-369723	-249701	1747068	31745	-95360
6116	401	369723	249701	-1919867	-31554	95355

Table C3 – Abnormal Sustained Extracted Forces and Moments, 900mmx300mm Sweepolet, Node 6070

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
15081	-283690	-362	-146420	3105	-240441	6766
15090	283690	362	146420	-3105	137070	-6511
15090	-239652	-666	-167508	3454	-100209	6691
15094	239652	666	167508	-3454	15617	-6354
15090	-30100	251	17290	-349	-36860	-180
15480	30100	-251	-17290	213	20606	180

Table C4 – Sustained Extracted Forces and Moments, 900mmx300mm Sweepolet, Node 15090

	Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
L4	15081	-812772	-894	-347182	8011	-507412	17125
	15090	812772	894	347182	-8011	262303	-16494
	15090	-702356	-1000	-394448	8236	-150877	16615
	15094	702356	1000	394448	-8236	-48320	-16110
	15090	-89357	69	38321	-225	-111425	-121
	15480	89357	-69	-38321	188	63172	121
L2	15081	76832	-117	42190	-990	70753	-1506
	15090	-76832	117	-42190	990	-40967	1588
	15090	65354	193	48869	-1145	31500	-1800
	15094	-65354	-193	-48869	1145	-6821	1702
	15090	7885	-271	-5478	155	9467	212
	15480	-7885	271	5478	-9	-5209	-212

Table C5 – Loadcase 9 (L4-L2), Shakedown, Extracted Forces and Moments, 900mmx300mm Sweepolet, Node 15090

1998 - 2003 Reverse Flow							
	Node	FX N.	FY N.	FZ N.	MX N.m.	MY N.m.	MZ N.m.
L8	6069	-21764	4023	136111	-650	91771	-4664
	6070	21764	-4023	-136111	650	-128521	5750
	6150	-138291	-101934	-3842326	-26814	-270362	19010
	6070	138291	101934	3842326	26875	277414	-19200
	6070	-166067	-97466	-3664461	-27525	-148893	13450
	6116	166067	97466	3664461	27949	227942	-15572
L9	6069	-21176	3932	132614	-629	89340	-4554
	6070	21176	-3932	-132614	629	-125146	5616
	6150	-135649	-100723	-3794576	-26241	-264803	18649
	6070	135649	100723	3794576	26298	271721	-18835
	6070	-162730	-96346	-3620913	-26928	-146576	13219
	6116	162730	96346	3620913	27328	224036	-15298
L10	6069	-18381	3694	114898	-51	76451	-4429
	6070	18381	-3694	-114898	51	-107474	5426
	6150	-125343	-84767	-3180388	-22386	-244190	17249
	6070	125343	84767	3180388	22417	250582	-17420
	6070	-149187	-80683	-3029581	-22468	-143108	11994
	6116	149187	80683	3029581	22769	214122	-13900
L11	6069	-6317	1073	39963	159	27332	-1200
	6070	6317	-1073	-39963	-159	-38122	1490
	6150	-33620	-16823	-630114	-5948	-64106	4657
	6070	33620	16823	630114	5953	65821	-4703
	6070	-41427	-15627	-578123	-5794	-27699	3213
	6116	41427	15627	578123	5741	47418	-3743
L12	6069	-6367	907	39651	-297	27398	-953
	6070	6367	-907	-39651	297	-38103	1198
	6150	-32940	-16545	-617343	-5733	-62904	4542

	6070	32940	16545	617343	5735	64584	-4587
	6070	-40768	-15517	-565858	-6031	-26481	3389
	6116	40768	15517	565858	5875	45887	-3910
1998 - 2003 Forward Flow							
L8	6069	6204	1265	38601	-182	30638	-999
	6070	-6204	-1265	-38601	182	-41060	1341
	6150	50448	-50414	-1913927	-20391	140854	-6965
	6070	-50448	50414	1913927	20439	-143426	7035
	6070	57917	-48989	-1864703	-20621	184487	-8375
	6116	-57917	48989	1864703	21126	-212055	9115
L9	6069	6604	1190	36037	-160	28852	-913
	6070	-6604	-1190	-36037	160	-38582	1234
	6150	52351	-48659	-1846342	-19949	144518	-7227
	6070	-52351	48659	1846342	19995	-147188	7299
	6070	60304	-47317	-1800454	-20155	185769	-8533
	6116	-60304	47317	1800454	20635	-214474	9303
L10	6069	9425	947	18295	419	15952	-782
	6070	-9425	-947	-18295	-419	-20892	1038
	6150	62815	-32721	-1232412	-16063	165472	-8649
	6070	-62815	32721	1232412	16081	-168676	8735
	6070	74036	-31676	-1209398	-15662	189567	-9773
	6116	-74036	31676	1209398	16036	-224809	10719
L11	6069	-1767	639	20004	312	13923	-625
	6070	1767	-639	-20004	-312	-19324	797
	6150	-9717	-16833	-610284	-5078	-11122	1356
	6070	9717	16833	610284	5055	11618	-1370
	6070	-12074	-16120	-584206	-4743	7706	572
	6116	12074	16120	584206	4534	-1959	-726
L12	6069	-1887	420	19912	-223	14168	-316

	6070	1887	-420	-19912	223	-19545	429
	6150	-9340	-16316	-594445	-4805	-10607	1292
	6070	9340	16316	594445	4786	11083	-1305
	6070	-11799	-15824	-568617	-5010	8462	876
	6116	11799	15824	568617	4742	-2846	-1027
2003 - 2021 Reverse Flow							
L8	6069	11638	-585	-60569	818	-46178	1447
	6070	-11638	585	60569	-818	62532	-1605
	6150	-48616	-29659	-1072027	-22703	33625	1841
	6070	48616	29659	1072027	22658	-31146	-1908
	6070	-39716	-30443	-1149389	-21839	-31386	3513
	6116	39716	30443	1149389	22033	50291	-4021
L9	6069	11580	-570	-59590	815	-45430	1422
	6070	-11580	570	59590	-815	61520	-1576
	6150	-47316	-29164	-1054774	-22375	34150	1783
	6070	47316	29164	1054774	22331	-31737	-1848
	6070	-38413	-29922	-1130878	-21516	-29783	3424
	6116	38413	29922	1130878	21722	48068	-3914
L10	6069	11268	-239	-51571	1071	-39683	940
	6070	-11268	239	51571	-1071	53608	-1005
	6150	-38703	-24765	-883556	-19434	36704	1441
	6070	38703	24765	883556	19380	-34730	-1494
	6070	-29764	-25129	-949214	-18310	-18878	2499
	6116	29764	25129	949214	18476	33046	-2879
L11	6069	904	-317	-13119	31	-10172	640
	6070	-904	317	13119	-31	13714	-726
	6150	-19252	-6761	-212063	-5027	-8231	1368
	6070	19252	6761	212063	4973	9213	-1395
	6070	-19361	-7151	-228860	-4942	-22927	2120

	6116	19361	7151	228860	4462	32143	-2368
L12	6069	931	-302	-12913	33	-10024	609
	6070	-931	302	12913	-33	13511	-691
	6150	-18783	-6577	-207507	-4869	-7725	1321
	6070	18783	6577	207507	4817	8683	-1347
	6070	-18845	-6955	-224033	-4785	-22194	2038
	6116	18845	6955	224033	4336	31164	-2278
2003 - 2021 Forward Flow							
L8	6069	8954	-1422	-54249	653	-38771	1871
	6070	-8954	1422	54249	-653	53418	-2256
	6150	4637	-21281	-696498	-15874	80907	-4345
	6070	-4637	21281	696498	15742	-81144	4351
	6070	13214	-23308	-766874	-15089	27725	-2096
	6116	-13214	23308	766874	13792	-34016	2264
L9	6069	7876	-926	-36727	573	-25405	1295
	6070	-7876	926	36727	-573	35321	-1545
	6150	27267	-11206	-346203	-10290	89387	-5360
	6070	-27267	11206	346203	10192	-90778	5397
	6070	35828	-12505	-394069	-9619	55457	-3852
	6116	-35828	12505	394069	8701	-72511	4309
L10	6069	8950	-567	-43429	1315	-31132	622
	6070	-8950	567	43429	-1315	42858	-775
	6150	19976	-14344	-447205	-11805	88709	-5061
	6070	-19976	14344	447205	11685	-89728	5088
	6070	29195	-15328	-503422	-10370	46870	-4314
	6116	-29195	15328	503422	9506	-60767	4687
L11	6069	1606	110	-12227	841	-9522	-34
	6070	-1606	-110	12227	-841	12824	64
	6150	-8297	-5569	-168730	-4400	4676	375

	6070	8297	5569	168730	4347	-4253	-387
	6070	-7216	-5517	-184318	-3506	-8571	323
	6116	7216	5517	184318	3234	12005	-415
L12	6069	1356	-204	-11765	262	-8846	470
	6070	-1356	204	11765	-262	12023	-525
	6150	-8319	-5485	-168887	-4286	4438	296
	6070	8319	5485	168887	4237	-4014	-307
	6070	-7487	-5756	-184018	-3976	-8009	832
	6116	7487	5756	184018	3587	11573	-928
2021 - 2050 Reverse Flow							
L8	6069	11647	-584	-60557	818	-46167	1447
	6070	-11647	584	60557	-818	62517	-1605
	6150	-48553	-29655	-1071961	-22706	33757	1835
	6070	48553	29655	1071961	22660	-31281	-1901
	6070	-39642	-30438	-1149308	-21842	-31237	3506
	6116	39642	30438	1149308	22038	50106	-4013
L9	6069	11589	-569	-59580	815	-45420	1422
	6070	-11589	569	59580	-815	61506	-1576
	6150	-47255	-29160	-1054713	-22378	34278	1776
	6070	47255	29160	1054713	22334	-31868	-1841
	6070	-38341	-29916	-1130805	-21519	-29638	3417
	6116	38341	29916	1130805	21727	47889	-3906
L10	6069	11274	-241	-51563	1071	-39676	941
	6070	-11274	241	51563	-1071	53598	-1007
	6150	-38660	-24766	-883513	-19429	36794	1436
	6070	38660	24766	883513	19375	-34822	-1489
	6070	-29714	-25132	-949162	-18305	-18776	2495
	6116	29714	25132	949162	18468	32919	-2875
L11	6069	908	-317	-13114	31	-10167	640

[redacted]

	6070	-908	317	13114	-31	13708	-725
	6150	-19224	-6759	-212038	-5028	-8173	1365
	6070	19224	6759	212038	4974	9153	-1392
	6070	-19328	-7148	-228828	-4943	-22861	2117
	6116	19328	7148	228828	4464	32061	-2364
L12	6069	935	-302	-12908	33	-10019	609
	6070	-935	302	12908	-33	13504	-691
	6150	-18756	-6575	-207482	-4870	-7668	1318
	6070	18756	6575	207482	4819	8624	-1344
	6070	-18812	-6953	-224002	-4786	-22129	2035
	6116	18812	6953	224002	4338	31084	-2275
2021 - 2050 Forward Flow							
L8	6069	8966	-1410	-54234	652	-38756	1863
	6070	-8966	1410	54234	-652	53400	-2244
	6150	4723	-21255	-696408	-15914	81091	-4351
	6070	-4723	21255	696408	15784	-81332	4357
	6070	13316	-23266	-766766	-15132	27932	-2113
	6116	-13316	23266	766766	13854	-34271	2284
L9	6069	7883	-919	-36719	572	-25397	1290
	6070	-7883	919	36719	-572	35311	-1538
	6150	27315	-11191	-346154	-10319	89489	-5364
	6070	-27315	11191	346154	10222	-90882	5401
	6070	35885	-12480	-394011	-9649	55572	-3863
	6116	-35885	12480	394011	8743	-72653	4322
L10	6069	8959	-559	-43419	1314	-31122	616
	6070	-8959	559	43419	-1314	42846	-767
	6150	20036	-14326	-447144	-11841	88837	-5065
	6070	-20036	14326	447144	11722	-89859	5093
	6070	29267	-15298	-503349	-10408	47014	-4326

	6116	-29267	15298	503349	9557	-60945	4700
L11	6069	1609	113	-12224	841	-9519	-37
	6070	-1609	-113	12224	-841	12819	67
	6150	-8277	-5562	-168710	-4415	4718	374
	6070	8277	5562	168710	4362	-4296	-385
	6070	-7192	-5506	-184294	-3521	-8523	318
	6116	7192	5506	184294	3255	11947	-410
L12	15981	6069	1359	-201	-11762	261	-8843
	15990	6070	-1359	201	11762	-261	12019
	15990	6150	-8299	-5478	-168866	-4301	4480
	16000	6070	8299	5478	168866	4253	-4057
	15990	6070	-7463	-5744	-183994	-3991	-7961
	16650	6116	7463	5744	183994	3608	11514

Table C6 – Fatigue Extracted Forces and Moments, 900mmx300mm Sweepolet

Load Type	Value	
	Node 25004	Node 25002
FX (N)	-249701	244247
FY (N)	-401	-437
FZ (N)	369723	-380703
MX (N.mm)	-9.5E+07	85405000
MY (N.mm)	1.75E+09	-1.8E+09
MZ (N.mm)	-3.2E+07	36807000

Table C7 – ABAQUS Input, Abnormal Sustained

Load Type	Value	
	Node 25004	Node 25002
FX (N)	239652	283690
FY (N)	167508	-146420
FZ (N)	666	-362
MX (N.mm)	3454000	-3105000
MY (N.mm)	-6691000	6511000
MZ (N.mm)	1E+08	-1.4E+08

Table C8 – ABAQUS Input, Sustained

	Load Type	Value	
		Node 25004	Node 25002
L4	FX (N)	702356	812772

	FY (N)	394448	-347182
	FZ (N)	1000	-894
	MX (N.mm)	8236000	-8011000
	MY (N.mm)	-1.7E+07	16494000
	MZ (N.mm)	1.51E+08	-2.6E+08
L2	FX (N)	-65354	-76832
	FY (N)	-48869	42190
	FZ (N)	-193	-117
	MX (N.mm)	-1145000	990000
	MY (N.mm)	1800000	-1588000
	MZ (N.mm)	-3.2E+07	40967000

Table C9 – ABAQUS Input, L9 (L4-L2), Shakedown

1998 - 2003 Reverse Flow										
	L8		L9		L10		L11		L12	
FX (N)	-3664461	3842326	-3620913	3794576	-3029581	3180388	-578123	630114	-565858	617343
FY (N)	-166067	138291	-162730	135649	-149187	125343	-41427	33620	-40768	32940
FZ (N)	97466	-101934	96346	-100723	80683	-84767	15627	-16823	15517	-16545
MX (N.mm)	13450000	-1.9E+07	13219000	-1.9E+07	11994000	-1.7E+07	3213000	-4703000	3389000	-4587000
MY (N.mm)	-2.8E+07	26875000	-2.7E+07	26298000	-2.2E+07	22417000	-5794000	5953000	-6031000	5735000
MZ (N.mm)	1.49E+08	-2.8E+08	1.47E+08	-2.7E+08	1.43E+08	-2.5E+08	27699000	-6.6E+07	26481000	-6.5E+07

1998 - 2003 Forward Flow										
	L8		L9		L10		L11		L12	
FX (N)	-1864703	1913927	-1800454	1846342	-1209398	1232412	-584206	610284	-568617	594445
FY (N)	57917	-50448	60304	-52351	74036	-62815	-12074	9717	-11799	9340
FZ (N)	48989	-50414	47317	-48659	31676	-32721	16120	-16833	15824	-16316
MX (N.mm)	-8375000	7035000	-8533000	7299000	-9773000	8735000	572000	-1370000	876000	-1305000
MY (N.mm)	-2.1E+07	20439000	-2E+07	19995000	-1.6E+07	16081000	-4743000	5055000	-5010000	4786000
MZ (N.mm)	-1.8E+08	1.43E+08	-1.9E+08	1.47E+08	-1.9E+08	1.69E+08	-7706000	-1.2E+07	-8462000	-1.1E+07

2003 - 2021 Reverse Flow										
	L8		L9		L10		L11		L12	
FX (N)	-1149389	1072027	-1130878	1054774	-949214	883556	-228860	212063	-224033	207507
FY (N)	-39716	48616	-38413	47316	-29764	38703	-19361	19252	-18845	18783
FZ (N)	30443	-29659	29922	-29164	25129	-24765	7151	-6761	6955	-6577
MX (N.mm)	3513000	-1908000	3424000	-1848000	2499000	-1494000	2120000	-1395000	2038000	-1347000
MY (N.mm)	-2.2E+07	22658000	-2.2E+07	22331000	-1.8E+07	19380000	-4942000	4973000	-4785000	4817000
MZ (N.mm)	31386000	31146000	29783000	31737000	18878000	34730000	22927000	-9213000	22194000	-8683000

2003 - 2021 Forward Flow										
	L8		L9		L10		L11		L12	

[redacted]

FX (N)	-766874	696498	-394069	346203	-503422	447205	-184318	168730	-184018	168887
FY (N)	13214	-4637	35828	-27267	29195	-19976	-7216	8297	-7487	8319
FZ (N)	23308	-21281	12505	-11206	15328	-14344	5517	-5569	5756	-5485
MX (N.mm)	-2096000	4351000	-3852000	5397000	-4314000	5088000	323000	-387000	832000	-307000
MY (N.mm)	-1.5E+07	15742000	-9619000	10192000	-1E+07	11685000	-3506000	4347000	-3976000	4237000
MZ (N.mm)	-2.8E+07	81144000	-5.5E+07	90778000	-4.7E+07	89728000	8571000	4253000	8009000	4014000
2021 - 2050 Reverse Flow										
	L8		L9		L10		L11		L12	
FX (N)	-1149308	1071961	-1130805	1054713	-949162	883513	-228828	212038	-224002	207482
FY (N)	-39642	48553	-38341	47255	-29714	38660	-19328	19224	-18812	18756
FZ (N)	30438	-29655	29916	-29160	25132	-24766	7148	-6759	6953	-6575
MX (N.mm)	3506000	-1901000	3417000	-1841000	2495000	-1489000	2117000	-1392000	2035000	-1344000
MY (N.mm)	-2.2E+07	22660000	-2.2E+07	22334000	-1.8E+07	19375000	-4943000	4974000	-4786000	4819000
MZ (N.mm)	31237000	31281000	29638000	31868000	18776000	34822000	22861000	-9153000	22129000	-8624000
2021 - 2050 Forward Flow										
	L8		L9		L10		L11		L12	
FX (N)	-766766	696408	-394011	346154	-503349	447144	-184294	168710	-183994	168866
FY (N)	13316	-4723	35885	-27315	29267	-20036	-7192	8277	-7463	8299
FZ (N)	23266	-21255	12480	-11191	15298	-14326	5506	-5562	5744	-5478
MX (N.mm)	-2113000	4357000	-3863000	5401000	-4326000	5093000	318000	-385000	827000	-305000
MY (N.mm)	-1.5E+07	15784000	-9649000	10222000	-1E+07	11722000	-3521000	4362000	-3991000	4253000
MZ (N.mm)	-2.8E+07	81332000	-5.6E+07	90882000	-4.7E+07	89859000	8523000	4296000	7961000	4057000

Table C10 – ABAQUS Input, Fatigue

[redacted]

	Normal Sustained Loadcase	Abnormal Sustained Loadcase
Loading Factor at Instability	1.66	1.69
TD/12 Factor	0.80	0.90
Limiting Loading Factor	1.33	1.52

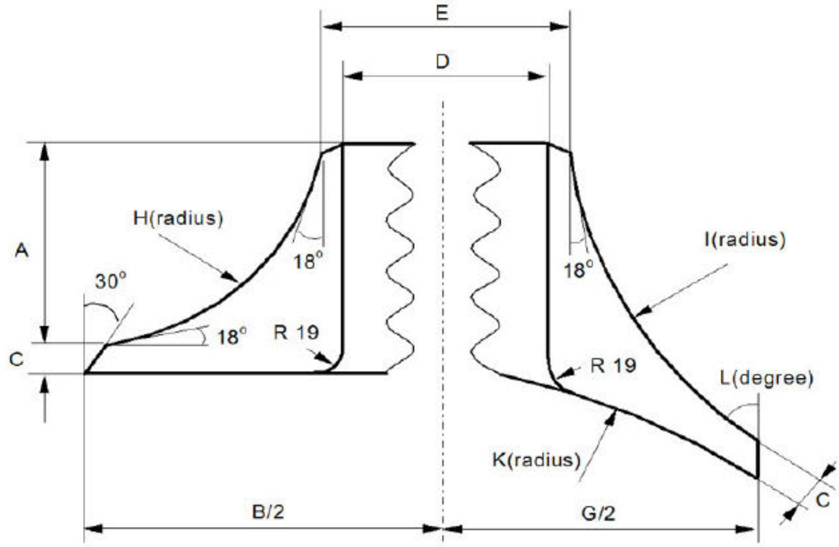
Table C11 – Limit Load Assessment

[redacted]

Caesar Model	Loadcase	Branch Weld				Header Weld				Crotch			
		Peak Stress	Allowable Cycles	Cycles	Usage	Peak Stress	Allowable Cycles	Cycles	Usage	Peak Stress	Allowable Cycles	Cycles	Usage
98-03R	L8	385.7	1.10E+04	4	3.63E-04	541	4.00E+03	4	1.00E-03	796.4	1.78E+03	4	2.24E-03
	L9	366.1	1.29E+04	27	2.09E-03	514.8	4.64E+03	27	5.82E-03	756.9	2.08E+03	27	1.30E-02
	L10	140.8	2.27E+05	675	2.98E-03	205.4	7.30E+04	675	9.24E-03	240.5	6.48E+04	675	1.04E-02
	L11	45.25	6.83E+06	5400	7.90E-04	75.27	1.48E+06	5400	3.64E-03	75.27	2.11E+06	5400	2.56E-03
	L12	43.6	7.64E+06	4050	5.30E-04	70.2	1.83E+06	4050	2.21E-03	70.2	2.61E+06	4050	1.55E-03
98-03F	L8	346.1	1.53E+04	0	0.00E+00	490.2	5.37E+03	0	0.00E+00	702.7	2.60E+03	0	0.00E+00
	L9	326.5	1.82E+04	2	1.10E-04	462.3	6.41E+03	2	3.12E-04	662.9	3.09E+03	2	6.46E-04
	L10	68.74	1.95E+06	53	2.72E-05	92.99	7.87E+05	53	6.73E-05	141	3.22E+05	53	1.65E-04
	L11	32.82	1.79E+07	81	4.52E-06	50.81	4.83E+06	81	1.68E-05	66.72	3.03E+06	81	2.67E-05
	L12	30.23	2.29E+07	265	1.16E-05	45.49	6.72E+06	265	3.94E-05	57.87	4.65E+06	265	5.70E-05
03-21R	L8	346.4	1.52E+04	0	0.00E+00	497.4	5.14E+03	0	0.00E+00	702.3	2.60E+03	0	0.00E+00
	L9	327.4	1.80E+04	1	5.54E-05	469.7	6.11E+03	1	1.64E-04	663.8	3.08E+03	1	3.25E-04
	L10	83.77	1.08E+06	5	4.64E-06	124.8	3.26E+05	5	1.54E-05	153.6	2.49E+05	5	2.01E-05
	L11	28.78	2.66E+07	31	1.17E-06	45.19	6.86E+06	31	4.52E-06	59.5	4.28E+06	31	7.25E-06
	L12	24.53	4.29E+07	139	3.24E-06	40.02	9.88E+06	139	1.41E-05	50.88	6.84E+06	139	2.03E-05
03-21F	L8	338.3	1.63E+04	4	2.45E-04	491.1	5.34E+03	4	7.48E-04	682.7	2.83E+03	4	1.41E-03
	L9	313.9	2.05E+04	22	1.07E-03	460	6.50E+03	22	3.38E-03	632.1	3.57E+03	22	6.17E-03
	L10	68.38	1.98E+06	502	2.54E-04	109.2	4.86E+05	502	1.03E-03	131.5	3.96E+05	502	1.27E-03
	L11	27.75	2.96E+07	765	2.58E-05	41.54	8.83E+06	765	8.66E-05	56.3	5.05E+06	765	1.51E-04
	L12	23.37	4.96E+07	2495	5.03E-05	36.96	1.25E+07	2495	1.99E-04	47.76	8.27E+06	2495	3.02E-04
21-50R	L8	346.4	1.52E+04	4	2.63E-04	497.4	5.14E+03	4	7.78E-04	702.3	2.60E+03	4	1.54E-03
	L9	327.4	1.80E+04	12	6.65E-04	469.7	6.11E+03	12	1.96E-03	663.8	3.08E+03	12	3.89E-03
	L10	83.76	1.08E+06	46	4.27E-05	124.8	3.26E+05	46	1.41E-04	153.6	2.49E+05	46	1.85E-04
	L11	28.77	2.66E+07	294	1.11E-05	45.18	6.86E+06	294	4.28E-05	59.49	4.28E+06	294	6.87E-05

	L12	24.53	4.29E+07	1310	3.05E-05	40.01	9.88E+06	1310	1.33E-04	50.87	6.85E+06	1310	1.91E-04
21-50F	L8	338.3	1.63E+04	20	1.22E-03	491	5.35E+03	20	3.74E-03	682.7	2.83E+03	20	7.06E-03
	L9	313.9	2.05E+04	1320	6.45E-02	460	6.50E+03	1320	2.03E-01	632	3.57E+03	1320	3.70E-01
	L10	68.37	1.98E+06	3100	1.57E-03	109.1	4.87E+05	3100	6.36E-03	131.4	3.97E+05	3100	7.80E-03
	L11	27.74	2.97E+07	4720	1.59E-04	41.53	8.84E+06	4720	5.34E-04	56.32	5.04E+06	4720	9.36E-04
	L12	23.36	4.97E+07	15390	3.10E-04	36.94	1.26E+07	15390	1.23E-03	47.76	8.27E+06	15390	1.86E-03
Cumulative Usage					**0.08**				**0.25**				**0.43**

Table C12 – Fatigue Results



A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	G (mm)	H (crotch radius)	I (flank radius)	K (mm)
84.1	521.0	15.9	304.9	323.9	450.0	40.5	70.0	441.3

Figure C1 – Sweepolet Geometry Dimensions

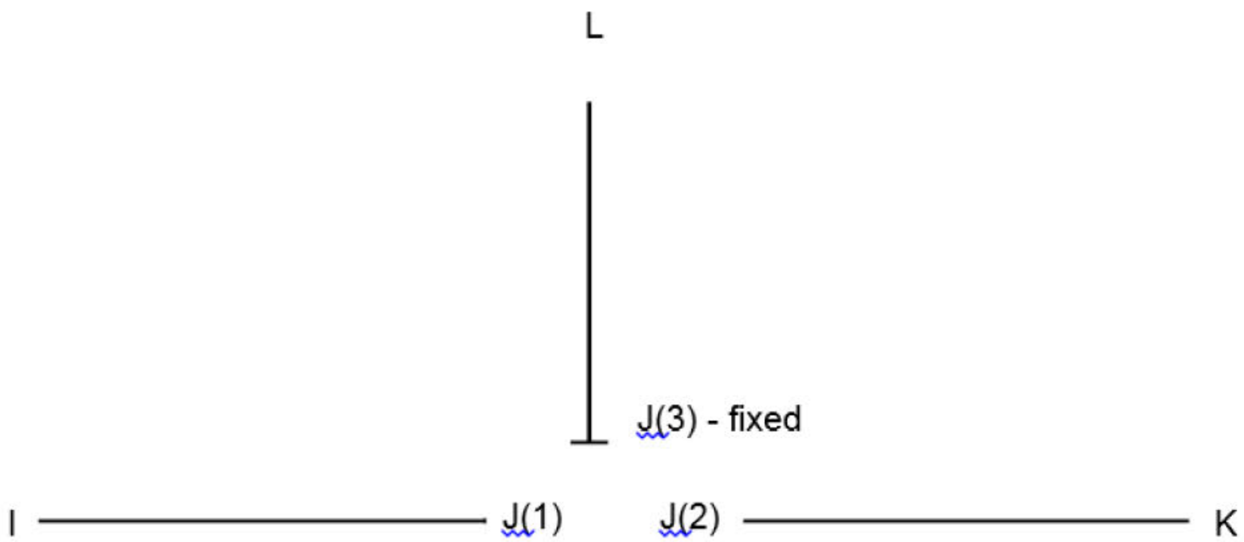
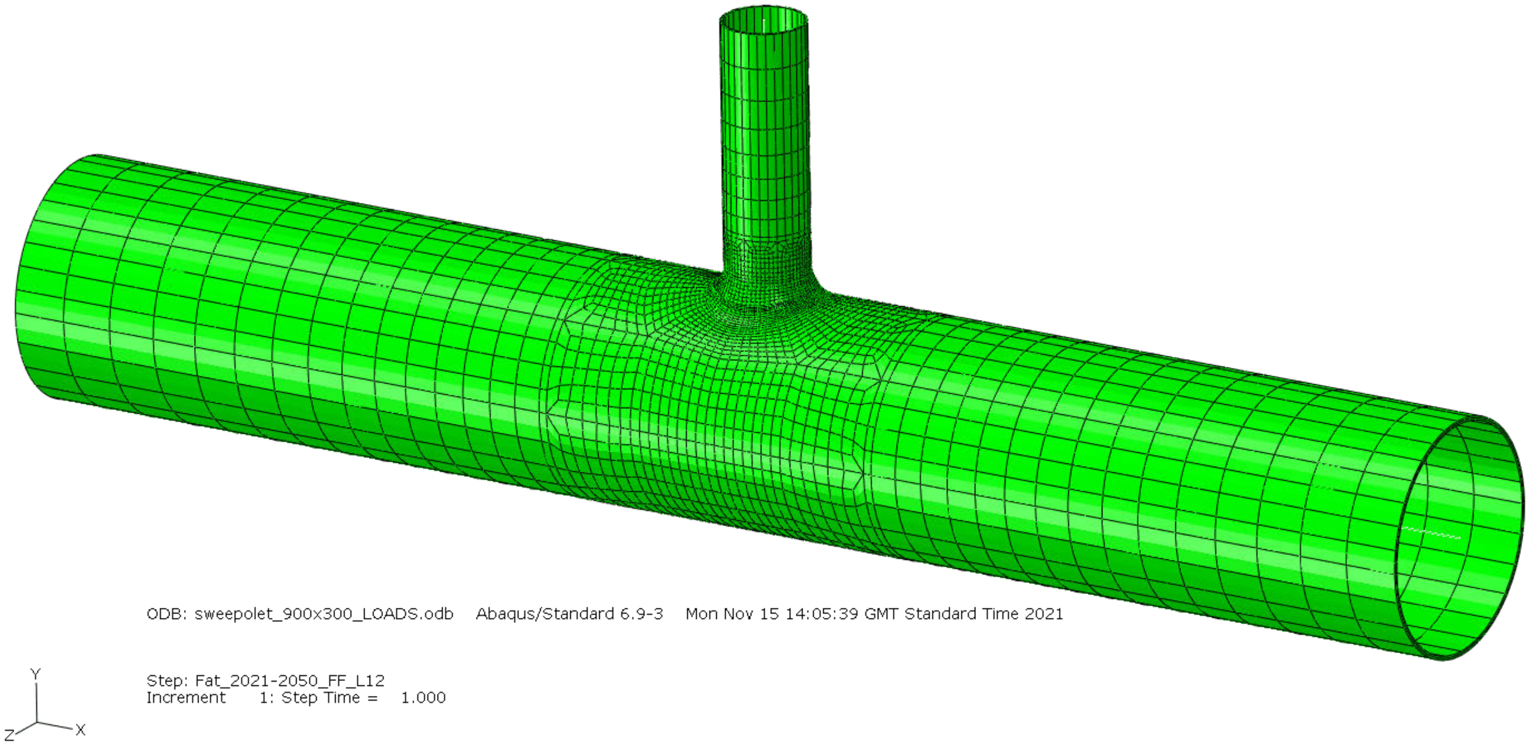
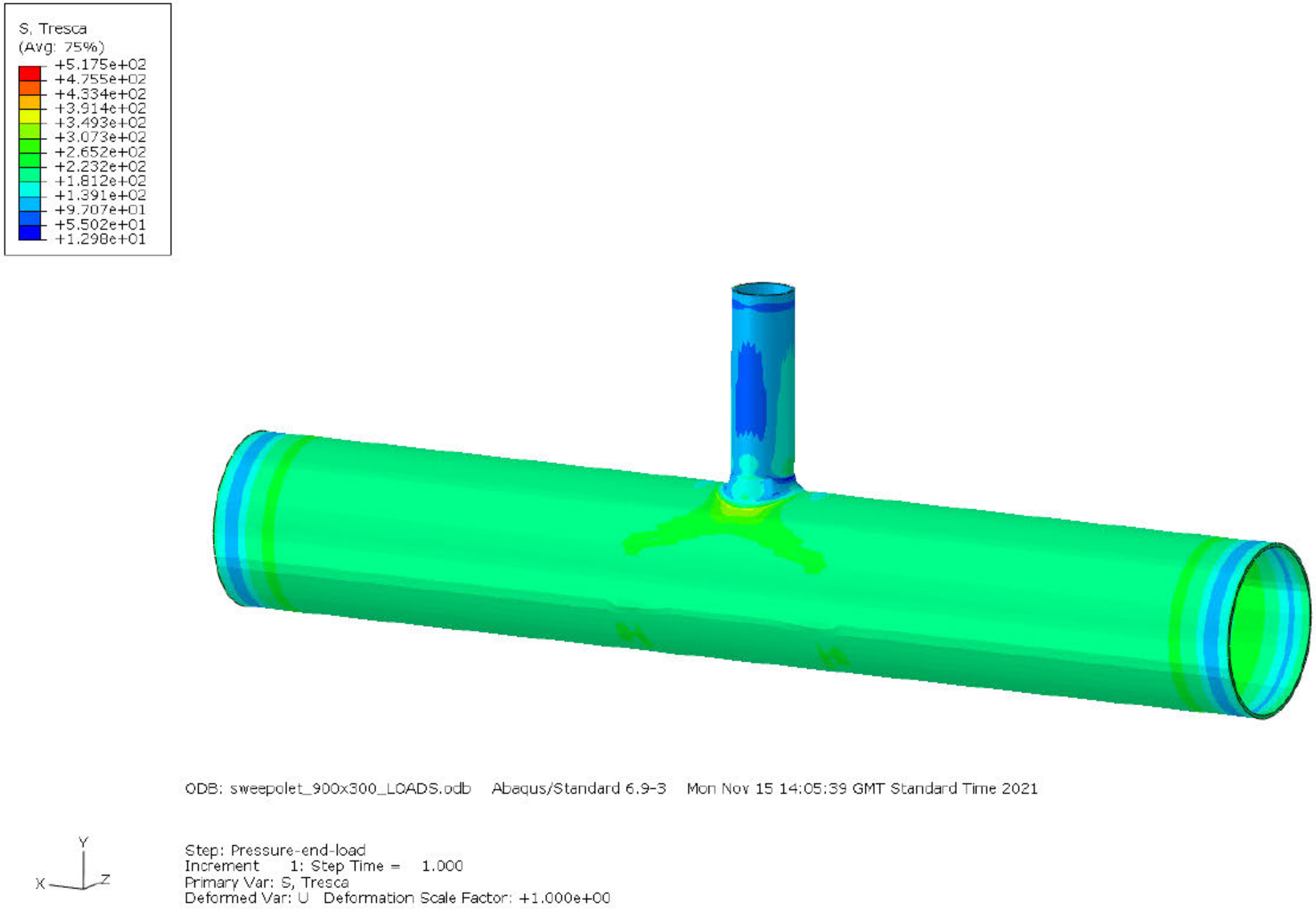


Figure C2 - Beam Schematic



<u>Figure C3 – 900mm x 300mm Sweepolet Mesh</u>



<u>Figure C4 – 900mm x 300mm – Max. Principal Stress – Pressure Only</u>

[redacted]

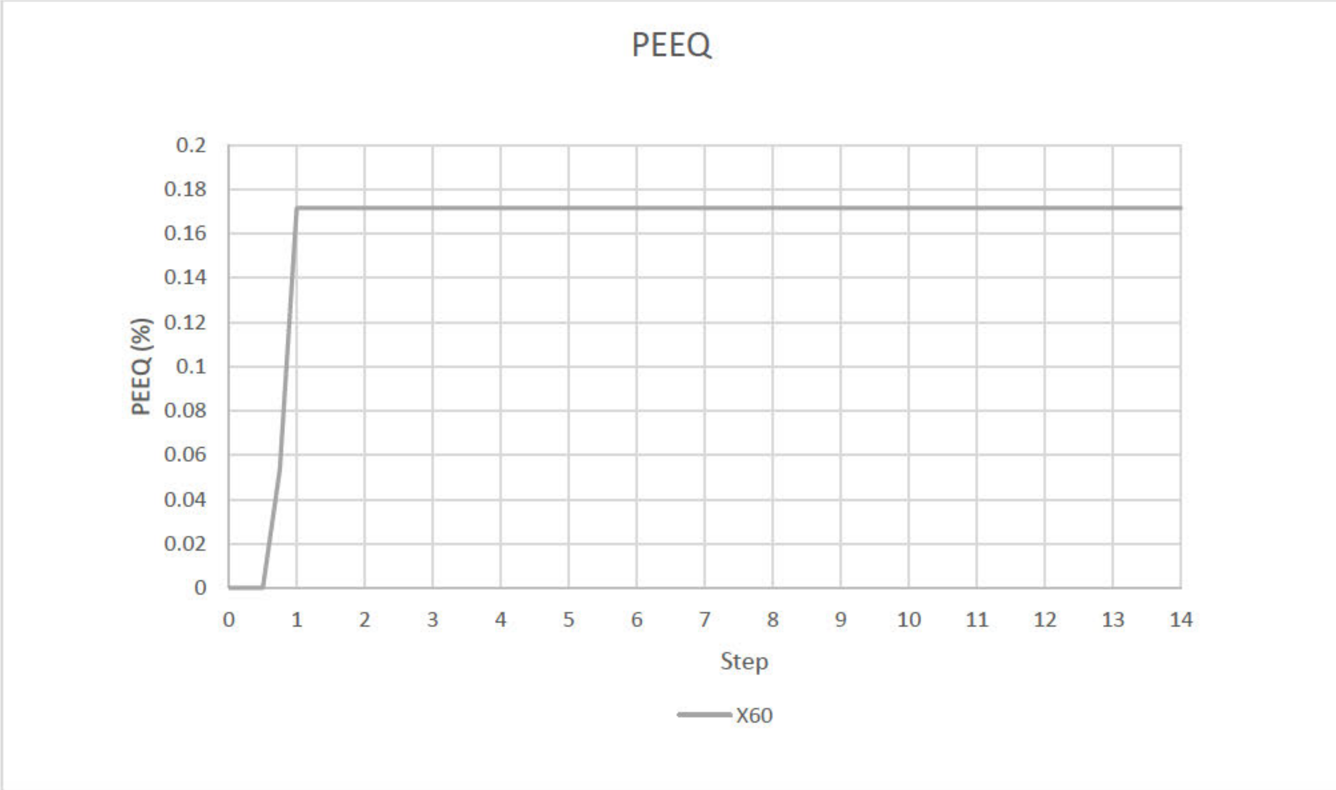


Figure C5 – Equivalent Plastic Strain (PEEQ) - Loadcase 9 – ASME VIII Incremental Plastic Collapse

[redacted]

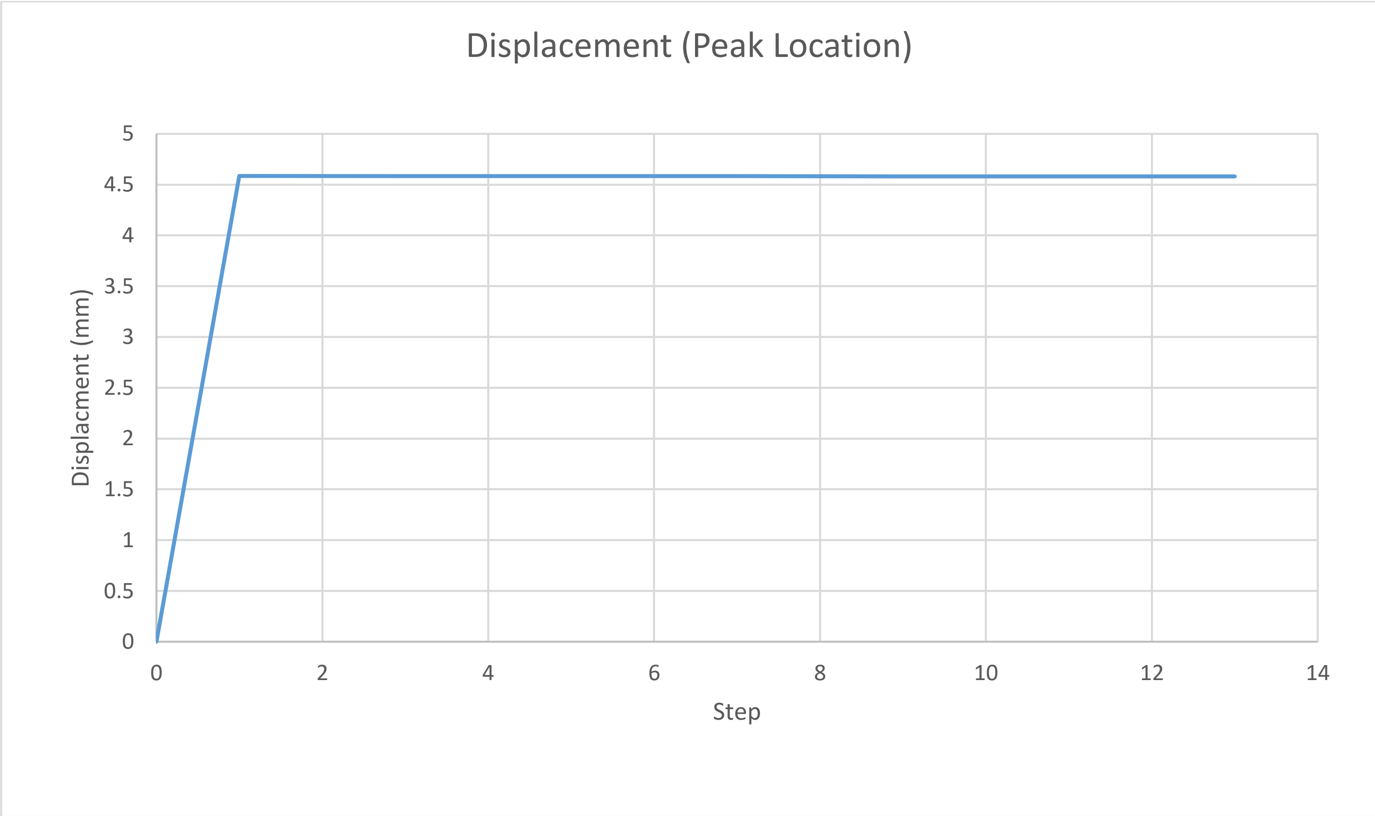


Figure C6 – Max. Displacement - Loadcase 9 – X60 Material Grade - ASME VIII Incremental Plastic Collapse

[redacted]

APPENDIX D 900MM X 200MM SWEEPOLET ASSESSMENT

D.1 GEOMETRY

In the absence of specific geometrical data the geometry of the sweepolet is assumed to meet the requirements of the 1971 edition of F1. The dimensions used are shown in Figure D1.

D.2 FINITE ELEMENT MODEL

The three-dimensional finite element (FE) model of the sweepolet was constructed using MSC Patran and analysed using the general purpose FE code ABAQUS. Twenty-noded, three degree of freedom reduced integration brick (hexahedral) elements, C3D20R, were used for the analysis.

Beam elements representing the pipe stress model are tied to the open ends of the 3D solid model using rigid multi-point constraints (MPCs), as shown schematically in Figure D2. The three nodes J(1), J(2) and J(3) are coincident at the intersection but are not connected. The branch node, J(3), is fixed by a translational and rotational boundary condition, whilst forces and moments are applied at the header nodes J(1) and J(2).

The beams allow the application of forces and moments from the pipe stress model onto the solid model of the fitting. Adequate lengths of header and branch pipe are modelled such that the local effects of the MPCs are removed from the area of interest at the fitting.

The FE mesh created for the 900mmx200mm sweepolet is shown in Figure D3.

D.3 MATERIAL PROPERTIES

Young's modulus and Poisson's ratio equal to 210000 N/mm^2 and 0.3, respectively, were used in all analyses. The material grade of the sweepolet is unknown and has therefore been modelled assuming minimum required mechanical properties as per F1 1972. A material grade of X60 has been assumed which has a SMYS of 413MPa and SMUTS of 517MPa.

Material property details for the sweepolet and matching header and branch are provided in Table D1.

D.4 LOADS

D.4.1 **Internal Pressure**

Distributed pressure loads were applied to all internal surfaces.

In order to represent the branch and one of the header sections being 'capped off' downstream of the fitting, pressure end loads were applied to the header pipe elements via the MPCs. The branch pressure end load was taken into consideration by the reaction at the branch boundary condition.

[redacted]

D.4.2 **System Forces and Moments**

For each of the assessment criteria considered, forces and moments were extracted for the most highly stressed fitting only, details of the IGE/TD/12 assessments considered and associated loadcase from the pipe stress analysis are provided in Table D2.

Before application to the FE model, the extracted forces and moments were converted to the axis convention of the FE model.

The extracted forces and moments are given in Table D3 to Table D6 and the forces and moments applied to the FE model are given in Table D7 to Table D10.

D.5 ANALYSIS

The assessment of the 900mmx900mm tee, of Appendix A, indicated very high stresses in the fitting which exceeded the linear elastic assessment criteria of IGE/TD/12, for both plastic collapse and shakedown. For this reason, and in order to obtain a more accurate solution, non-linear analyses have been undertaken to determine the acceptability of the 900mmx200mm sweepolet.

D.5.1 **Plastic Collapse (Limit Load Analysis)**

Protection against plastic collapse is demonstrated by undertaking an elastic-perfectly-plastic (limit load) analysis to determine the load which causes overall structural instability.

D.5.2 **Shakedown (Incremental Plastic Collapse)**

IGE/TD/12 does not provided guidance for undertaking a non-linear analysis to consider shakedown loads, therefore an elastic-perfectly-plastic analysis has been performed in accordance with ASME VIII Division 2. Details of the assessment are provided in Section 3.2.1.

D.6 RESULTS

D.6.1 **Internal Pressure**

A contour plot of maximum principal stresses due to an internal pressure loading of 79.5 barg is presented in Figure D3. Away from concentrations, maximum principal stress in the adjoining pipe is in the range 200 to 230 MPa. Classical theory predicts a hoop stress of 228.6 MPa in the outside wall for a wall thickness of 15.9 mm. This provides some confidence in the model.

D.6.2 **Sustained**

D.6.2.6 **Limit Load Analysis**

Table D11 summarises the results of the assessment, limiting loading factors of 1.57 and 1.46 were found for the abnormal and normal sustained loadcases, and therefore the sweepolet is fit for purpose for the anticipated sustained loadings.

[redacted]

D.6.3 **Shakedown**

Only the most highly stressed region, located at the sweepolet crotch, has been considered for assessment. From Figure D5, it is shown that for an assumed minimum material grade of X60, shakedown is successfully achieved.

Figure D6 shows the maximum predicted displacement of the fitting for thirteen repeat load cycles. It is shown that the predicted displacement does not change significantly from the first to last load cycle. It can thus be inferred that the overall dimensions of the fitting have not changed and the tee satisfies the ASME VIII elastic-plastic ratcheting criteria.

D.6.4 **Fatigue**

Table D13 shows the results of the fatigue assessment, the maximum past + future cumulative usage was calculated to be 0.45 at the sweepolet crotch, and therefore the sweepolet is considered to be fit for purpose for the past and anticipated future fatigue duties.

[redacted]

D.7 CONCLUSIONS

1. A three-dimensional finite element model of the 900mmx200mm sweepolet has been created.

2. System forces and moments, giving rise to the sustained, shakedown and fatigue exceptions have been extracted from the relevant pipe stress model and applied on the FE model together with internal pressure.

3. Finite element analysis of the 900mmx200mm sweepolet has been undertaken using the ABAQUS software, with a subsequent limit load and fatigue assessment to the TD/12 DBA criterion for sustained and fatigue loadcases only.

4. In lieu of a TD/12 elastic-plastic shakedown criterion, an incremental plastic collapse assessment has been undertaken to the requirements of ASME VIII Division 2.

5. Limiting loading factors of 1.57 and 1.46 were found for the normal and abnormal sustained loadcases, and therefore the sweepolet is fit for purpose for the anticipated sustained loadings.

6. The 900mmx200mm sweepolet has been shown to satisfy the DBA fatigue criterion of TD/12.

7. The 900mmx200mm sweepolet has been shown to satisfy the elastic-plastic incremental plastic collapse criterion of ASME VIII Div 2.

[redacted]

Matching Pipe			Branch Pipe			Sweepolet		Material Grade	
								X60	
Diameter	Wall Thickness	Material Grade	Diameter	Wall Thickness	Material Grade	Crotch Thickness	Crotch Radius	SMYS	UTS
914.4	15.9	X60	31.3	945.2	X60	41.5	19	413	517

Figure D1 – 900mm x 200mm Sweepolet Details

Assessment	Reported Code Stress Ratio (%)	Usage	Model Name	Node Number
Abnormal Sustained	255.31	-	KL_CLAY_SETTLEMENT_FF_01	1310
Sustained	111.84	-	KL_FIRM_CLAY_FF_01_PITS_SOFT_FILL	15990
Shakedown	164.47	-	KL_CLAY_SETTLEMENT_RF_01	15990
Fatigue	-	14.18	1971_FIRM_CLAY 1998_RF_FIRM_CLAY 1998_FF_FIRM_CLAY 2003-2021_RF_FIRM_CLAY 2003-2021_FF_FIRM_CLAY 2021-2050_X10_RF_FIRM_CLAY_NO_PITS_SOFT_FILL 2021-2050_X10_FF_FIRM_CLAY_NO_PITS_SOFT_FILL	15990

Figure D2 – Loadcases Assessed

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
1300	58706	87219	-15287	-217261	-56186	-80188
1310	-58706	-87219	15287	217355	63064	119797
1310	45920	175628	-12967	-283474	-64215	-125143
1320	-45920	-175628	12967	284042	105708	689156
1310	1457	-47865	-1571	66119	1150	5346
1570	-1457	47865	1571	-40606	-374	-5346

Table D3 – Abnormal Sustained Extracted Forces and Moments, 900mmx200mm Sweepolet, Node 1310

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
15981	598736	14	1645	-208	138970	-1154
15990	-598736	-14	-1645	208	-144217	1197
15990	672524	-135	899	-218	129886	-1281
16000	-672524	135	-899	218	-131698	1008
15990	-12229	69	-2598	10	14330	83
16650	12229	-69	2598	27	-7812	-83

Table D4 – Sustained Extracted Forces and Moments, 900mmx200mm Sweepolet, Node 15990

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
15980	531776	320	74174	1034	25081	319
15990	-531776	-320	-74174	-1034	-498389	1723
15990	826762	89	-17926	1214	406325	-1687
16000	-826762	-89	17926	-1214	-370204	1866
15990	-91795	77	32211	-180	92064	-37
16650	91795	-77	-32211	221	-43137	37

Table D5 – Loadcase 9, Shakedown, Extracted Forces and Moments, 900mmx200mm Sweepolet, Node 15990

1971 - 1998							
	Node	FX N.	FY N.	FZ N.	MX N.m.	MY N.m.	MZ N.m.
L8	15980	1546224	785	67477	-206	44524	1145
	15990	-1546224	-785	-67477	206	-475094	3862
	15990	1974454	-327	26567	-360	315462	-3848
	16000	-1974454	327	-26567	360	-368994	3188

[redacted]

	15990	-176007	430	-823	154	159632	-14
	16650	176007	-430	823	75	-65820	14
L9	15980	1517156	767	65888	-198	44759	1114
	15990	-1517156	-767	-65888	198	-465192	3781
	15990	1939532	-321	25967	-349	310028	-3767
	16000	-1939532	321	-25967	349	-362353	3121
	15990	-171245	421	-892	151	155164	-14
	16650	171245	-421	892	74	-63889	14
L10	15980	1262638	644	55549	-181	36767	929
	15990	-1262638	-644	-55549	181	-391228	3177
	15990	1608157	-269	21293	-307	260282	-3181
	16000	-1608157	269	-21293	307	-303188	2639
	15990	-141378	344	-146	126	130946	3
	16650	141378	-344	146	57	-55591	-3
L11	15980	313195	171	15902	-95	4373	234
	15990	-313195	-171	-15902	95	-105846	859
	15990	376129	-71	5771	-122	63964	-861
	16000	-376129	71	-5771	122	-75591	717
	15990	-45128	85	183	26	41883	2
	16650	45128	-85	-183	19	-17829	-2
L12	15980	307543	170	15619	-91	4223	238
	15990	-307543	-170	-15619	91	-103890	846
	15990	368445	-70	5667	-119	62671	-848
	16000	-368445	70	-5667	119	-74090	706
	15990	-44416	85	174	27	41219	2
	16650	44416	-85	-174	18	-17545	-2
1998 - 2003 Reverse Flow							
L8	15981	1606953	-39	18841	-1076	423959	-3406
	15990	-1606953	39	-18841	1076	-484073	3281

	15990	1954578	-245	13938	-727	325401	-3245
	16000	-1954578	245	-13938	727	-353487	2751
	15990	-175784	-169	-3280	-349	158672	-36
	16650	175784	169	3280	258	-64978	36
L9	15981	1576919	-38	18270	-1046	415242	-3335
	15990	-1576919	38	-18270	1046	-473533	3214
	15990	1918333	-241	13575	-706	319520	-3178
	16000	-1918333	241	-13575	706	-346873	2693
	15990	-170738	-164	-3276	-340	154013	-35
	16650	170738	164	3276	252	-63008	35
L10	15981	1287131	-40	14914	-895	344679	-2798
	15990	-1287131	40	-14914	895	-392262	2669
	15990	1562029	-199	10478	-608	264174	-2656
	16000	-1562029	199	-10478	608	-285288	2255
	15990	-138816	-152	-2078	-288	128088	-13
	16650	138816	152	2078	207	-54098	13
L11	15981	306827	-8	4625	-287	91813	-774
	15990	-306827	8	-4625	287	-106568	749
	15990	364492	-54	2897	-204	64745	-747
	16000	-364492	54	-2897	204	-70583	637
	15990	-45232	-44	-359	-83	41823	-2
	16650	45232	44	359	59	-17714	2
L12	15981	300899	-8	4533	-281	89991	-756
	15990	-300899	8	-4533	281	-104454	731
	15990	356760	-53	2839	-200	63357	-729
	16000	-356760	53	-2839	200	-69076	622
	15990	-44446	-43	-356	-81	41097	-2
	16650	44446	43	356	58	-17407	2

[redacted]

1998 - 2003 Forward Flow							
L8	15981	767185	-144	3855	-718	205809	-1682
	15990	-767185	144	-3855	718	-218108	1222
	15990	918717	-59	2980	-415	158141	-1189
	16000	-918717	59	-2980	415	-164146	1071
	15990	-68837	-237	-2019	-304	59967	-33
	16650	68837	237	2019	177	-23276	33
L9	15981	734482	-141	3441	-696	198024	-1622
	15990	-734482	141	-3441	696	-209003	1171
	15990	879488	-56	2741	-401	151659	-1136
	16000	-879488	56	-2741	401	-157182	1024
	15990	-66299	-229	-2091	-295	57345	-35
	16650	66299	229	2091	173	-22007	35
L10	15981	444721	-144	84	-545	127463	-1085
	15990	-444721	144	-84	545	-127730	627
	15990	523215	-14	-356	-302	96319	-614
	16000	-523215	14	356	302	-95602	585
	15990	-34368	-217	-893	-243	31411	-13
	16650	34368	217	893	127	-13093	13
L11	15981	252287	-20	2359	-190	63172	-532
	15990	-252287	20	-2359	190	-70697	467
	15990	304181	-30	1788	-118	50097	-462
	16000	-304181	30	-1788	118	-53699	402
	15990	-22462	-48	-472	-72	20600	-4
	16650	22462	48	472	46	-8628	4
L12	15981	244973	-21	2278	-187	61387	-516
	15990	-244973	21	-2278	187	-68654	449
	15990	295327	-28	1727	-116	48664	-445
	16000	-295327	28	-1727	116	-52143	388

	15990	-21793	-48	-462	-71	19990	-4
	16650	21793	48	462	45	-8374	4
2003 - 2021 Reverse Flow							
L8	15981	1606805	-39	18910	-1078	424009	-3407
	15990	-1606805	39	-18910	1078	-484343	3282
	15990	1954857	-246	14006	-727	325127	-3246
	16000	-1954857	246	-14006	727	-353349	2751
	15990	-176218	-168	-3270	-351	159216	-36
	16650	176218	168	3270	261	-65290	36
L9	15981	1576776	-38	18337	-1048	415291	-3336
	15990	-1576776	38	-18337	1048	-473794	3215
	15990	1918603	-241	13640	-706	319254	-3180
	16000	-1918603	241	-13640	706	-346739	2693
	15990	-171159	-163	-3267	-342	154540	-35
	16650	171159	163	3267	255	-63311	35
L10	15981	1287023	-40	14972	-897	344722	-2799
	15990	-1287023	40	-14972	897	-392489	2670
	15990	1562245	-199	10532	-608	263953	-2657
	16000	-1562245	199	-10532	608	-285175	2255
	15990	-139141	-151	-2065	-289	128536	-13
	16650	139141	151	2065	209	-54373	13
L11	15981	306763	-8	4644	-288	91819	-774
	15990	-306763	8	-4644	288	-106636	749
	15990	364551	-54	2916	-204	64669	-747
	16000	-364551	54	-2916	204	-70545	637
	15990	-45338	-44	-356	-84	41966	-2
	16650	45338	44	356	60	-17801	2
L12	15981	300837	-8	4552	-282	89998	-757
	15990	-300837	8	-4552	282	-104520	731

[redacted]

	15990	356819	-53	2857	-200	63282	-728
	16000	-356819	53	-2857	200	-69039	621
	15990	-44549	-43	-354	-82	41238	-2
	16650	44549	43	354	59	-17493	2
2003 - 2021 Forward Flow							
L8	15981	767075	-145	3884	-722	205801	-1682
	15990	-767075	145	-3884	722	-218194	1220
	15990	918786	-58	3008	-416	158025	-1187
	16000	-918786	58	-3008	416	-164085	1069
	15990	-69025	-238	-2015	-306	60170	-33
	16650	69025	238	2015	179	-23379	33
L9	15981	189917	-111	-2948	-334	66441	-595
	15990	-189917	111	2948	334	-57034	242
	15990	217605	3	-2286	-177	46021	-227
	16000	-217605	-3	2286	177	-41415	233
	15990	-14550	-147	-1070	-157	11013	-15
	16650	14550	147	1070	78	-3258	15
L10	15981	336012	-129	-1565	-432	103236	-871
	15990	-336012	129	1565	432	-98243	461
	15990	398632	-8	-660	-227	73725	-432
	16000	-398632	8	660	227	-72395	416
	15990	-32471	-179	-2192	-206	24518	-29
	16650	32471	179	2192	111	-7211	29
L11	15981	209640	-11	1459	-144	54862	-463
	15990	-209640	11	-1459	144	-59516	428
	15990	258248	-31	1908	-88	40722	-410
	16000	-258248	31	-1908	88	-44566	348
	15990	-25198	-25	-1659	-55	18795	-18
	16650	25198	25	1659	42	-5364	18

[redacted]

L12	15981	209638	-12	1459	-146	54859	-464
	15990	-209638	12	-1459	146	-59515	424
	15990	258240	-30	1908	-89	40722	-406
	16000	-258240	30	-1908	89	-44566	345
	15990	-25190	-26	-1658	-57	18793	-18
	16650	25190	26	1658	43	-5366	18
2021 - 2050 Reverse Flow							
L8	15981	1656998	63	2924	-678	414404	-3577
	15990	-1656998	-63	-2924	678	-423733	3779
	15990	1836778	-452	1675	-822	374150	-4106
	16000	-1836778	452	-1675	822	-377525	3196
	15990	-42296	267	-10871	144	49584	327
	16650	42296	-267	10871	-1	-27040	-327
L9	15981	1624826	61	2846	-659	405886	-3499
	15990	-1624826	-61	-2846	659	-414965	3693
	15990	1803207	-441	1697	-799	366849	-4012
	16000	-1803207	441	-1697	799	-370269	3124
	15990	-41044	258	-10628	140	48116	319
	16650	41044	-258	10628	-2	-26240	-319
L10	15981	1324816	46	1794	-561	337049	-2946
	15990	-1324816	-46	-1794	561	-342773	3094
	15990	1466116	-373	1246	-695	301668	-3378
	16000	-1466116	373	-1246	695	-304179	2626
	15990	-35059	217	-9640	134	41105	284
	16650	35059	-217	9640	-18	-22418	-284
L11	15981	326519	25	186	-177	90738	-838
	15990	-326519	-25	-186	177	-91330	919
	15990	339581	-115	-294	-228	77567	-1009
	16000	-339581	115	294	228	-76974	778

	15990	-11734	81	-2904	51	13762	90
	16650	11734	-81	2904	-8	-7508	-90
L12	15981	320191	24	174	-174	88935	-821
	15990	-320191	-24	-174	174	-89489	898
	15990	333032	-112	-289	-224	75959	-986
	16000	-333032	112	289	224	-75376	760
	15990	-11536	79	-2864	50	13530	89
	16650	11536	-79	2864	-8	-7381	-89
2021 - 2050 Forward Flow							
L8	15981	791938	-58	-2093	-459	203730	-1759
	15990	-791938	58	2093	459	-197053	1575
	15990	880472	-184	-2392	-414	179454	-1687
	16000	-880472	184	2392	414	-174634	1316
	15990	-14948	38	-3499	-45	17599	112
	16650	14948	-38	3499	65	-9631	-112
L9	15981	196840	-65	-4079	-209	67268	-623
	15990	-196840	65	4079	209	-54253	417
	15990	211235	-52	-3600	-159	51033	-445
	16000	-211235	52	3600	159	-43779	340
	15990	-2671	-26	-893	-49	3220	28
	16650	2671	26	893	35	-1796	-28
L10	15981	348710	-72	-3889	-245	103284	-948
	15990	-348710	72	3889	245	-90875	717
	15990	381703	-91	-3382	-220	83913	-740
	16000	-381703	91	3382	220	-77098	556
	15990	-5880	1	-1851	-25	6962	23
	16650	5880	-1	1851	26	-3828	-23
L11	15981	218041	-2	-201	-82	53977	-496
	15990	-218041	2	201	82	-53335	491

[redacted]

	15990	243692	-58	-105	-89	48096	-508
	16000	-243692	58	105	89	-47885	391
	15990	-4469	21	-1348	7	5239	18
	16650	4469	-21	1348	5	-2857	-18
L12	15981	218047	-2	-202	-86	53981	-496
	15990	-218047	2	202	86	-53337	489
	15990	243698	-57	-105	-91	48098	-507
	16000	-243698	57	105	91	-47886	392
	15990	-4469	20	-1348	6	5238	18
	16650	4469	-20	1348	5	-2857	-18

Table D6 – Fatigue Extracted Forces and Moments, 900mmx200mm Swepolet

Load Type	Value	
	Node 25004	Node 25002
FX (N)	-58706	45920
FY (N)	-15287	12967
FZ (N)	87219	-175628
MX (N.mm)	2.17E+08	-2.8E+08
MY (N.mm)	-1.2E+08	1.25E+08
MZ (N.mm)	-6.3E+07	64215000

Table D7 – ABAQUS Input, Abnormal Sustained

Load Type	Value	
	Node 25004	Node 25002
FX (N)	-672524	598736
FY (N)	899	-1645
FZ (N)	135	14
MX (N.mm)	218000	-208000
MY (N.mm)	-1281000	1197000
MZ (N.mm)	-1.3E+08	1.44E+08

Table D8 – ABAQUS Input, Sustained

Load Type	Value	
	Node 25004	Node 25002
FX (N)	-826762	531776
FY (N)	-17926	-74174
FZ (N)	-89	320
MX (N.mm)	-1214000	1034000
MY (N.mm)	-1687000	1723000
MZ (N.mm)	-4.1E+08	4.98E+08

Table D9 – ABAQUS Input, L9, Shakedown

[redacted]

1971 - 1998										
Load Type	L8		L9		L10		L11		L12	
	Node 25004	**Node 25002**	**Node 25004**	**Node 25002**	**Node 25004**	**Node 25002**	**Node 25004**	**Node 25002**	**Node 25004**	**Node 25002**
FX (N)	-1974454	1546224	-1939532	1517156	-1608157	1262638	-376129	313195	-368445	307543
FY (N)	26567	67477	25967	-65888	21293	-55549	5771	-15902	5667	-15619
FZ (N)	327	785	321	767	269	644	71	171	70	170
MX (N.mm)	360000	-206000	349000	-198000	307000	-181000	122000	-95000	119000	-91000
MY (N.mm)	-3848000	3862000	-3767000	3781000	-3181000	3177000	-861000	859000	-848000	846000
MZ (N.mm)	-3.2E+08	4.75E+08	-3.1E+08	4.65E+08	-2.6E+08	3.91E+08	-6.4E+07	1.06E+08	-6.3E+07	1.04E+08
1998 - 2003 Reverse Flow										
	L8		L9		L10		L11		L12	
FX (N)	-1954578	1606953	-1918333	1576919	-1562029	1287131	-364492	306827	-356760	300899
FY (N)	13938	-18841	13575	-18270	10478	-14914	2897	-4625	2839	-4533
FZ (N)	245	-39	241	-38	199	-40	54	-8	53	-8
MX (N.mm)	727000	-1076000	706000	-1046000	608000	-895000	204000	-287000	200000	-281000
MY (N.mm)	-3245000	3281000	-3178000	3214000	-2656000	2669000	-747000	749000	-729000	731000
MZ (N.mm)	-3.3E+08	4.84E+08	-3.2E+08	4.74E+08	-2.6E+08	3.92E+08	-6.5E+07	1.07E+08	-6.3E+07	1.04E+08
1998 - 2003 Forward Flow										
	L8		L9		L10		L11		L12	
FX (N)	-918717	767185	-879488	734482	-523215	444721	-304181	252287	-295327	244973
FY (N)	2980	-3855	2741	-3441	-356	-84	1788	-2359	1727	-2278
FZ (N)	59	-144	56	-141	14	-144	30	-20	28	-21
MX (N.mm)	415000	-718000	401000	-696000	302000	-545000	118000	-190000	116000	-187000
MY (N.mm)	-1189000	1222000	-1136000	1171000	-614000	627000	-462000	467000	-445000	449000
MZ (N.mm)	-1.6E+08	2.18E+08	-1.5E+08	2.09E+08	-9.6E+07	1.28E+08	-5E+07	70697000	-4.9E+07	68654000
2003 - 2021 Reverse Flow										

[redacted]

	L8		L9		L10		L11		L12	
FX (N)	-1954857	1606805	-1918603	1576776	-1562245	1287023	-364551	306763	-356819	300837
FY (N)	14006	-18910	13640	-18337	10532	-14972	2916	-4644	2857	-4552
FZ (N)	246	-39	241	-38	199	-40	54	-8	53	-8
MX (N.mm)	727000	-1078000	706000	-1048000	608000	-897000	204000	-288000	200000	-282000
MY (N.mm)	-3246000	3282000	-3180000	3215000	-2657000	2670000	-747000	749000	-728000	731000
MZ (N.mm)	-3.3E+08	4.84E+08	-3.2E+08	4.74E+08	-2.6E+08	3.92E+08	-6.5E+07	1.07E+08	-6.3E+07	1.05E+08
2003 - 2021 Forward Flow										
	L8		L9		L10		L11		L12	
FX (N)	-918786	767075	-217605	189917	-398632	336012	-258248	209640	-258240	209638
FY (N)	3008	-3884	-2286	2948	-660	1565	1908	-1459	1908	-1459
FZ (N)	58	-145	-3	-111	8	-129	31	-11	30	-12
MX (N.mm)	416000	-722000	177000	-334000	227000	-432000	88000	-144000	89000	-146000
MY (N.mm)	-1187000	1220000	-227000	242000	-432000	461000	-410000	428000	-406000	424000
MZ (N.mm)	-1.6E+08	2.18E+08	-4.6E+07	57034000	-7.4E+07	98243000	-4.1E+07	59516000	-4.1E+07	59515000
2021 - 2050 Reverse Flow										
	L8		L9		L10		L11		L12	
FX (N)	-1836778	1656998	-1803207	1624826	-1466116	1324816	-339581	326519	-333032	320191
FY (N)	1675	-2924	1697	-2846	1246	-1794	-294	-186	-289	-174
FZ (N)	452	63	441	61	373	46	115	25	112	24
MX (N.mm)	822000	-678000	799000	-659000	695000	-561000	228000	-177000	224000	-174000
MY (N.mm)	-4106000	3779000	-4012000	3693000	-3378000	3094000	-1009000	919000	-986000	898000
MZ (N.mm)	-3.7E+08	4.24E+08	-3.7E+08	4.15E+08	-3E+08	3.43E+08	-7.8E+07	91330000	-7.6E+07	89489000
2021 - 2050 Forward Flow										
	L8		L9		L10		L11		L12	
FX (N)	-880472	791938	-211235	196840	-381703	348710	-243692	218041	-243698	218047

[redacted]

FY (N)	-2392	2093	-3600	4079	-3382	3889	-105	201	-105	202
FZ (N)	184	-58	52	-65	91	-72	58	-2	57	-2
MX (N.mm)	414000	-459000	159000	-209000	220000	-245000	89000	-82000	91000	-86000
MY (N.mm)	-1687000	1575000	-445000	417000	-740000	717000	-508000	491000	-507000	489000
MZ (N.mm)	-1.8E+08	1.97E+08	-5.1E+07	54253000	-8.4E+07	90875000	-4.8E+07	53335000	-4.8E+07	53337000

Table D10 – ABAQUS Input, Fatigue

	Normal Sustained Loadcase	Abnormal Sustained Loadcase
Loading Factor at Instability	1.82	1.74
TD/12 Factor	0.8	0.9
Limiting Loading Factor	1.46	1.57

Table D11 – Limit Load Assessment

Region	Primary + Secondary Membrane + Bending (MPa)	Allowable Stress (MPa) (3f)	Margin on Incremental Plastic Collapse
Shakedown - Branch Pipe	482.1	660.0	1.37
Shakedown - Header Pipe	598.4	660.0	1.10
Shakedown - Crotch	660.8	660.0	1.00

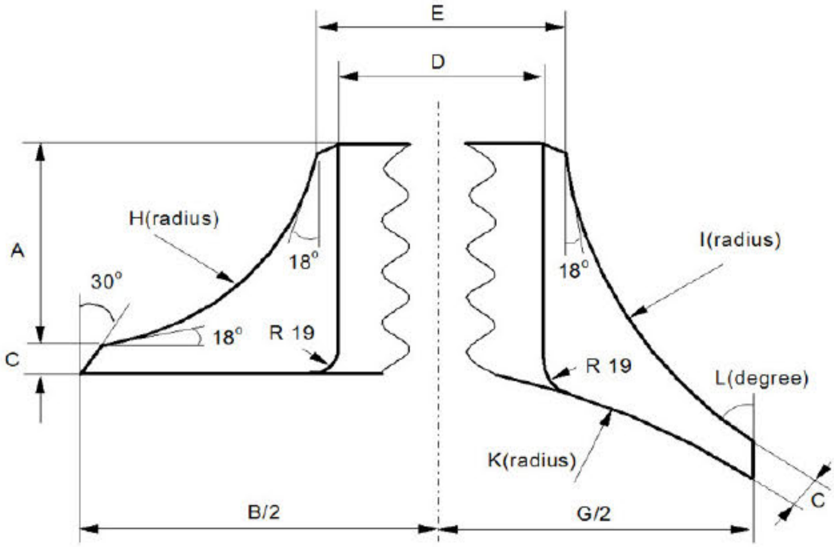
Table D12 – Shakedown Results

Caesar Model	Loadcase	Branch Weld				Header Weld				Crotch			
		Peak Stress	Allowable Cycles	Cycles	Usage	Peak Stress	Allowable Cycles	Cycles	Usage	Peak Stress	Allowable Cycles	Cycles	Usage
71-98	L8	599.9	2.93E+03	4	1.36E-03	436.1	7.63E+03	4	5.24E-04	709.2	2.65E+03	4	1.51E-03
	L9	592.5	3.04E+03	27	8.87E-03	421.8	8.43E+03	27	3.20E-03	673	3.10E+03	27	8.72E-03

	L10	320.2	1.93E+04	675	3.50E-02	107.2	5.14E+05	675	1.31E-03	176.7	1.71E+05	675	3.94E-03
	L11	65.11	2.29E+06	5400	2.35E-03	91.95	8.14E+05	5400	6.63E-03	54.24	5.92E+06	5400	9.12E-04
	L12	64.64	2.34E+06	4050	1.73E-03	90.24	8.61E+05	4050	4.70E-03	46.62	9.32E+06	4050	4.35E-04
98-03R	L8	379.1	1.16E+04	0	0.00E+00	427.1	8.12E+03	0	0.00E+00	680.6	3.00E+03	0	0.00E+00
	L9	371.9	1.23E+04	2	1.63E-04	398.9	9.97E+03	2	2.01E-04	643.8	3.54E+03	2	5.65E-04
	L10	137.5	2.43E+05	53	2.18E-04	113.5	4.33E+05	53	1.22E-04	145.1	3.09E+05	53	1.71E-04
	L11	78.37	1.32E+06	81	6.16E-05	112	4.51E+05	81	1.80E-04	55.24	5.60E+06	81	1.45E-05
	L12	77.23	1.37E+06	265	1.93E-04	109.2	4.86E+05	265	5.45E-04	51.52	6.91E+06	265	3.84E-05
98-03F	L8	351.4	1.46E+04	0	0.00E+00	429.3	8.00E+03	0	0.00E+00	668.4	3.16E+03	0	0.00E+00
	L9	333.1	1.71E+04	1	5.84E-05	405.6	9.49E+03	1	1.05E-04	630.8	3.76E+03	1	2.66E-04
	L10	98.7	6.58E+05	5	7.59E-06	86.95	9.63E+05	5	5.19E-06	131.6	4.14E+05	5	1.21E-05
	L11	53.77	4.07E+06	31	7.61E-06	36.8	1.27E+07	31	2.44E-06	54.73	5.76E+06	31	5.38E-06
	L12	49.6	5.19E+06	139	2.68E-05	31.52	2.02E+07	139	6.88E-06	46.44	9.43E+06	139	1.47E-05
03-21R	L8	377.5	1.18E+04	4	3.40E-04	428.2	8.06E+03	4	4.96E-04	680.4	3.00E+03	4	1.33E-03
	L9	370.4	1.25E+04	22	1.77E-03	399.8	9.91E+03	22	2.22E-03	643.7	3.54E+03	22	6.21E-03
	L10	136.1	2.51E+05	502	2.00E-03	115	4.16E+05	502	1.21E-03	144.9	3.10E+05	502	1.62E-03
	L11	78.8	1.29E+06	765	5.91E-04	112.5	4.45E+05	765	1.72E-03	55.29	5.59E+06	765	1.37E-04
	L12	77.66	1.35E+06	2495	1.85E-03	109.7	4.79E+05	2495	5.20E-03	51.78	6.80E+06	2495	3.67E-04
03-21F	L8	350.9	1.47E+04	4	2.73E-04	429.1	8.01E+03	4	4.99E-04	668.4	3.16E+03	4	1.26E-03
	L9	267.1	3.32E+04	12	3.61E-04	393	1.04E+04	12	1.15E-03	619.3	3.98E+03	12	3.02E-03
	L10	90.71	8.48E+05	46	5.42E-05	88.25	9.21E+05	46	4.99E-05	130	4.30E+05	46	1.07E-04
	L11	53.86	4.05E+06	294	7.26E-05	39.18	1.05E+07	294	2.79E-05	54.4	5.87E+06	294	5.01E-05
	L12	50.73	4.85E+06	1310	2.70E-04	34.09	1.60E+07	1310	8.20E-05	46.29	9.52E+06	1310	1.38E-04
21-50R	L8	479.8	5.73E+03	20	3.49E-03	493.7	5.26E+03	20	3.80E-03	682.4	2.97E+03	20	6.73E-03
	L9	469.4	6.12E+03	1320	2.16E-01	474.7	5.92E+03	1320	2.23E-01	645.7	3.51E+03	1320	3.76E-01
	L10	218.2	6.09E+04	3100	5.09E-02	154.2	1.73E+05	3100	1.80E-02	150.1	2.79E+05	3100	1.11E-02
	L11	53.63	4.10E+06	4720	1.15E-03	63.93	2.42E+06	4720	1.95E-03	53.6	6.13E+06	4720	7.70E-04

	L12	49.92	5.09E+06	15390	3.02E-03	59.35	3.03E+06	15390	5.08E-03	45.39	1.01E+07	15390	1.52E-03
21-50F	L8	396.6	1.01E+04	20	1.97E-03	469.9	6.10E+03	20	3.28E-03	670	3.14E+03	20	6.37E-03
	L9	267.2	3.32E+04	70	2.11E-03	396.8	1.01E+04	70	6.91E-03	619.2	3.98E+03	70	1.76E-02
	L10	100.2	6.29E+05	290	4.61E-04	101.6	6.04E+05	290	4.80E-04	129.9	4.31E+05	290	6.73E-04
	L11	60.95	2.80E+06	1810	6.47E-04	52.88	4.28E+06	1810	4.23E-04	54.54	5.82E+06	1810	3.11E-04
	L12	57.84	3.27E+06	8090	2.47E-03	48.52	5.54E+06	8090	1.46E-03	46.58	9.34E+06	8090	8.66E-04
Cumulative Usage					**0.34**				**0.29**				**0.45**

Table D13 –Fatigue Results



A (mm)	**B** (mm)	**C** (mm)	**D** (mm)	**E** (mm)	**G** (mm)	**H** (crotch radius)	**I** (flank radius)	**K** (mm)
76.2	381	15.9	202.7	219.1	357	27.4	70	441.3

Figure D1 – Sweepolet Geometry Dimensions

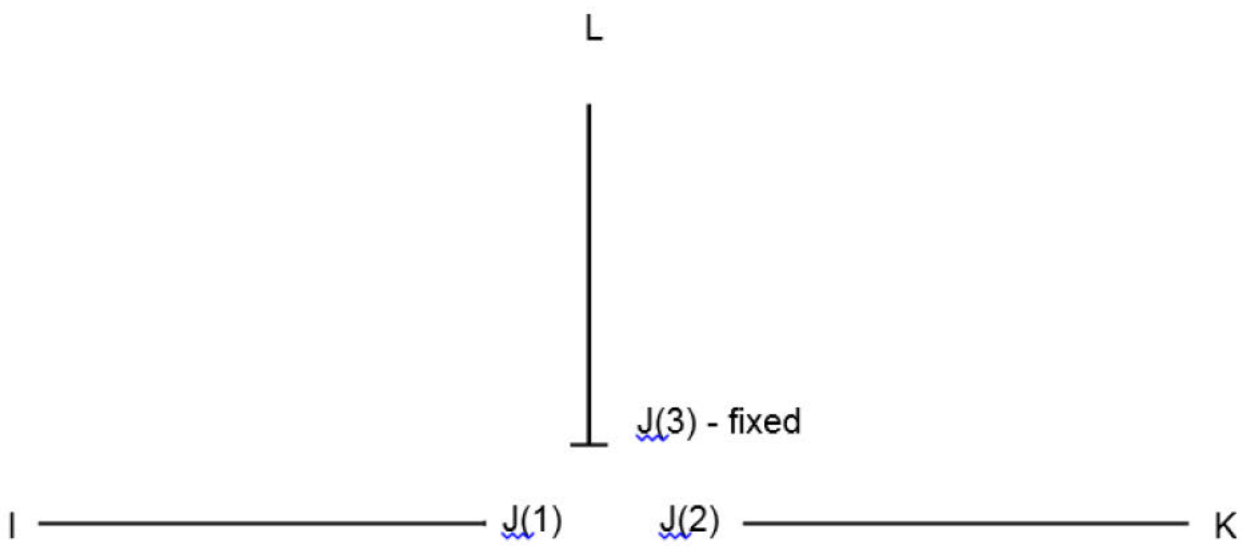


Figure D2 - Beam Schematic

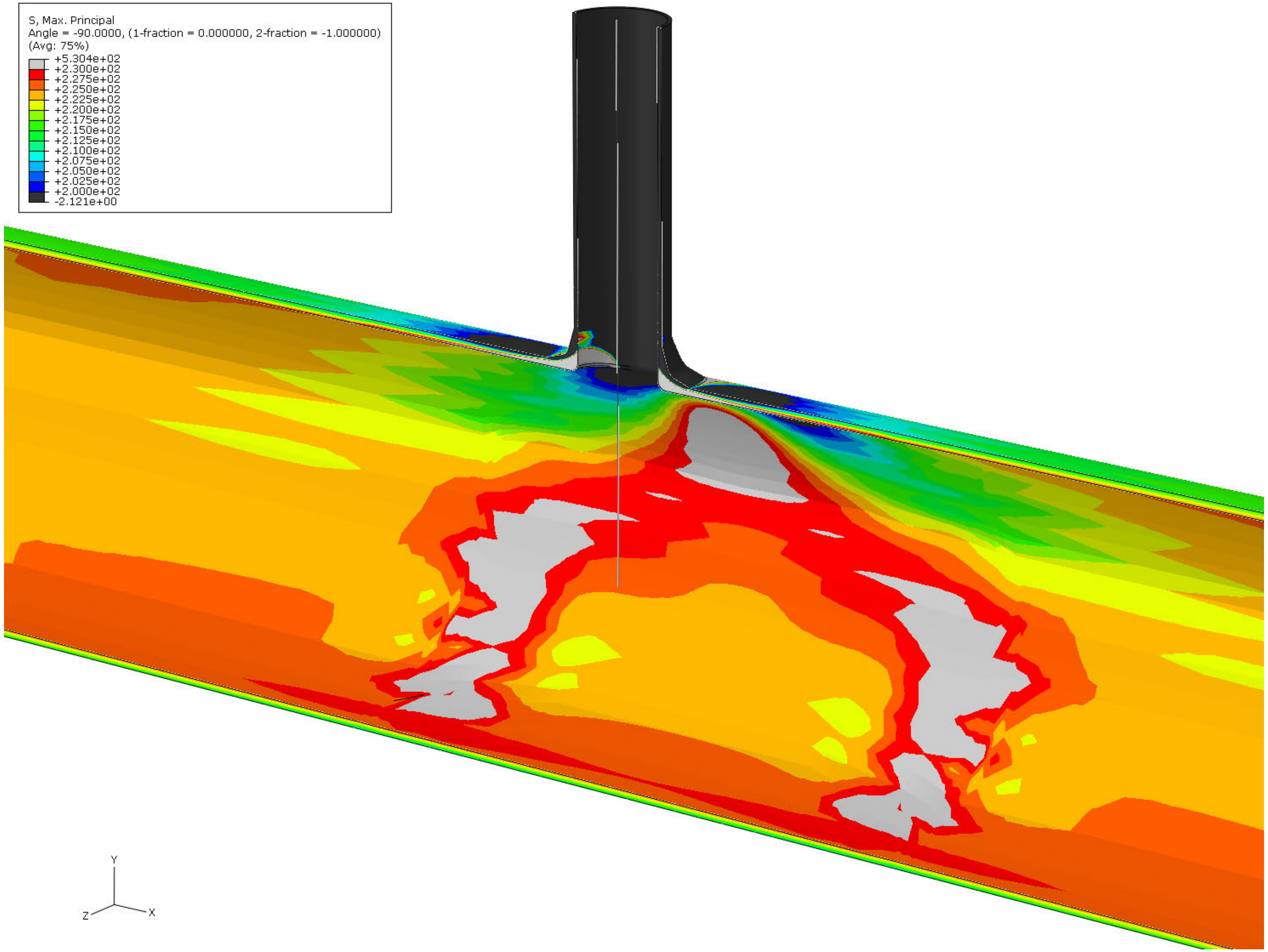


Figure D3 – Max. Principal Stress Due to 79.5 barg

[redacted]

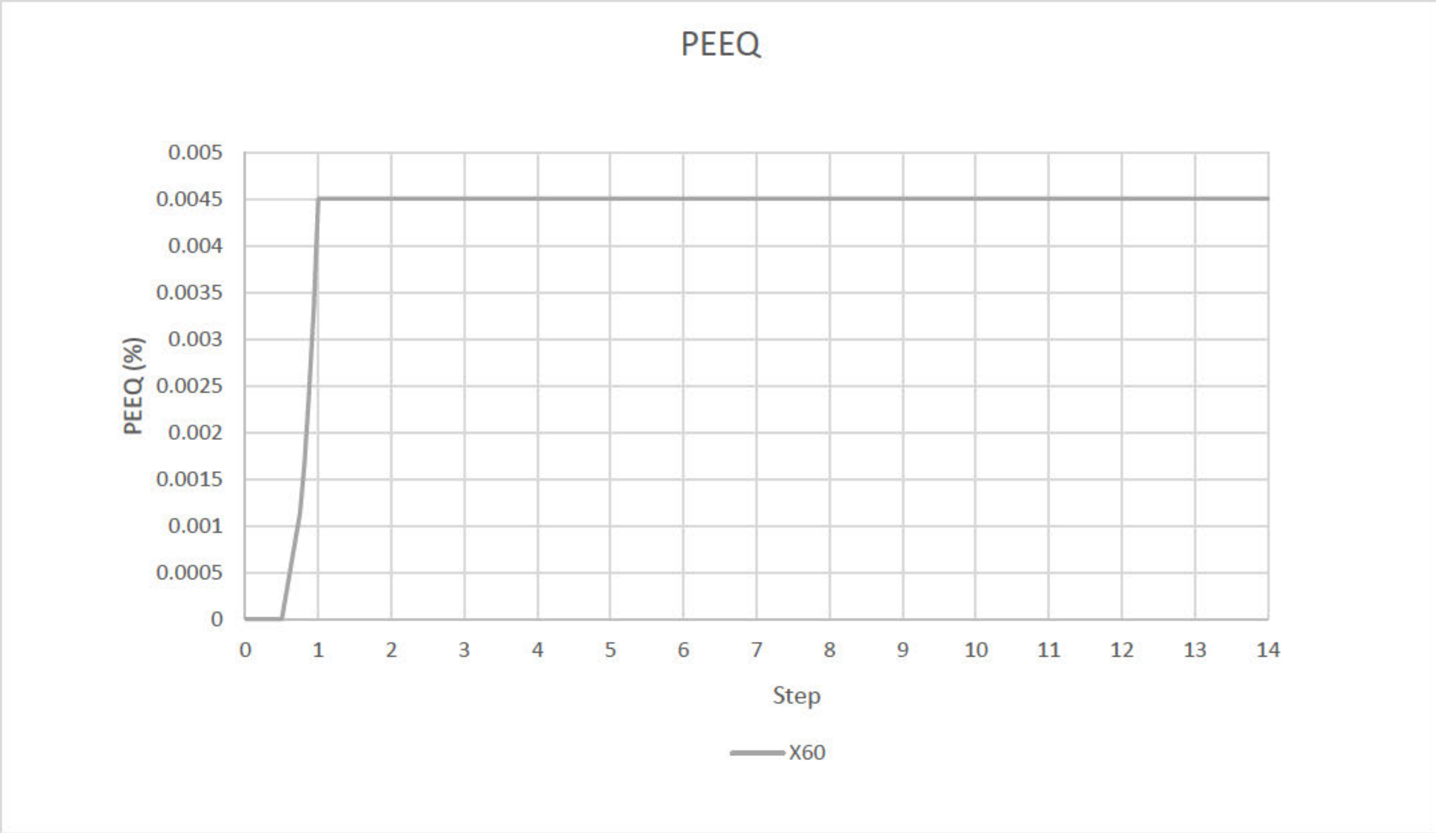


Figure D4 – Equivalent Plastic Strain (PEEQ) - Loadcase 9 – ASME VIII Incremental Plastic Collapse

[redacted]

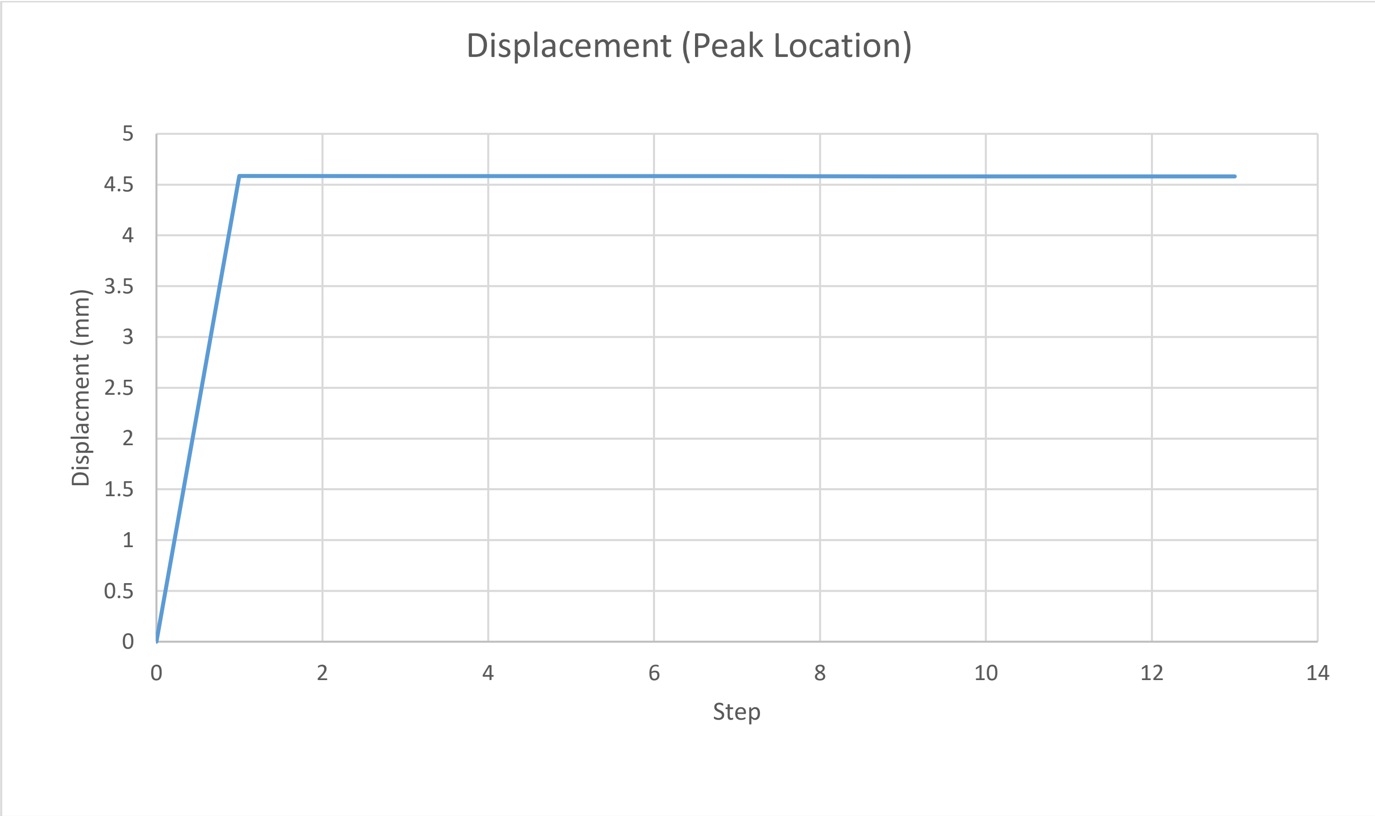


Figure D5 – Max. Displacement - Loadcase 9 – X60 Material Grade - ASME VIII Incremental Plastic Collapse

[redacted]

APPENDIX E 900MM X 50MM WELDOLET ASSESSMENT

E.1 GEOMETRY

In the absence of specific geometrical data the geometry of the weldolet is assumed to satisfy the requirements of the 1971 edition of F1. The properties used are shown in Table E1.

E.2 FINITE ELEMENT MODEL

The three dimensional finite element (FE) model of the weldolet was constructed using MSC Patran and analysed using the general purpose FE code ABAQUS. Twenty-noded, three degree of freedom reduced integration brick (hexahedral) elements, C3D20R, were used for the analysis.

Beam elements representing the pipe stress model are tied to the open ends of the 3D solid model using rigid multi-point constraints (MPCs), as shown schematically in Figure E1. The three nodes J(1), J(2) and J(3) are coincident at the intersection but are not connected. The branch node, J(3), is fixed by a translational and rotational boundary condition, whilst forces and moments are applied at the header nodes J(1) and J(2).

The beams allow the application of forces and moments from the pipe stress model onto the solid model of the fitting. Adequate lengths of header and branch pipe are modelled such that the local effects of the MPCs are removed from the area of interest at the fitting.

The FE mesh created for the 900mmx50mm weldolet is shown in Figure E2.

E.3 MATERIAL PROPERTIES

Young's modulus and Poisson's ratio equal to 210000 N/mm^2 and 0.3, respectively, were used in all analyses. The actual material grade of the weldolet is unknown and has therefore been modelled assuming minimum required mechanical properties as per F1 1972. A material grade of X60 has been assumed which has a SMYS of 413MPa and SMUTS of 517MPa.

Material property details for the sweepolet and matching header and branch are provided in Table E1.

E.4 LOADS

E.4.1 **Internal Pressure**

Distributed pressure loads were applied to all internal surfaces.

In order to represent the branch and one of the header sections being 'capped off' downstream of the fitting, pressure end loads were applied to the header pipe

[redacted]

elements via the MPCs. The branch pressure end load was taken into consideration by the reaction at the branch boundary condition.

E.4.2 **System Forces and Moments**

For the assessment criteria considered, forces and moments were extracted for the most highly stressed fitting only, details of the IGE/TD/12 assessments considered and associated loadcase from the pipe stress analysis are provided in Table E2.

Before application to the FE model, the extracted forces and moments were converted to the axis convention of the FE model.

The extracted forces and moments are given in Table E3 and the forces and moments applied to the FE model are given in Table E4.

E.5 ANALYSIS

The assessment of the 900mmx900mm tee, of Appendix A, indicated very high stresses in the fitting which exceeded the linear elastic assessment criteria of IGE/TD/12, for both plastic collapse and shakedown. For this reason, and in order to obtain a more accurate solution, non-linear analyses have been undertaken to determine the acceptability of the 900mmx50mm weldolet.

E.5.1 **Plastic Collapse (Limit Load Analysis)**

Protection against plastic collapse is demonstrated by undertaking an elastic-perfectly-plastic (limit load) analysis to determine the load which causes overall structural instability.

E.6 RESULTS

E.6.1 **Internal Pressure**

A contour plot of maximum principal stresses due to an internal pressure loading of 79.5 barg is presented in Figure E3. Away from concentrations, maximum principal stress in the adjoining pipe is in the range 200 to 230 MPa. Classical theory predicts a hoop stress of 228.6 MPa in the outside wall for a wall thickness of 15.9 mm. This provides some confidence in the model.

E.6.2 **Sustained**

E.6.2.7 **Limit Load Analysis**

Table E5 summarises the results of the assessment, a limiting loading factor of 1.58 was found for the abnormal sustained loadcase, and therefore the weldolet is fit for purpose for the anticipated abnormal sustained loadings.

[redacted]

E.7 CONCLUSIONS

1. A three-dimensional finite element model of the 900mmx50mm weldolet has been created.

2. System forces and moments, giving rise to the sustained and shakedown exceptions have been extracted from the relevant pipe stress model and applied on the FE model together with internal pressure.

3. Finite element analysis of the 900mmx50mm weldolet has been undertaken using the ABAQUS software, with a subsequent limit load assessment to the TD/12 DBA criterion for sustained loading.

4. A limiting loading factor of 1.58 was found for the abnormal sustained loadcase, and therefore the weldolet is fit for purpose for the anticipated abnormal sustained loadings.

[redacted]

Header Pipe			Branch Pipe			Weldolet	Material Grade	
Diameter	Wall Thickness	Material Grade	Diameter	Wall Thickness	Material Grade	Material Grade	X60	
							SMYS	UTS
914.4	15.9	X60	60.3	5.5	B	X60	413	517

Table E1 – 900mm x 50mm Weldolet Details

Assessment	Reported Code Stress Ratio (%)	Usage	Model Name	Node Number
Abnormal Sustained	105.97	-	KL_CLAY_SETTLEMENT_FF_01	6160

Table E2 – Loadcases Assessed

[redacted]

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
6116	-503	-369630	-251042	1920059	31692	-95346
6160	503	369630	251042	-1920421	-31692	95346
6160	-2004	-369145	-254890	1917504	31716	-94329
6165	2004	369145	254890	-1917866	-31714	94329
6160	1355	-362	3534	1300	-24	-398
8690	-1355	362	-3534	-1166	24	346

Table E3 – Abnormal Sustained Extracted Forces and Moments, 900mmx50mm weldolet, Node 6160

Load Type	Value	
	Node 100004	Node 100002
FX (N)	-254890	251042
FY (N)	369145	-369630
FZ (N)	2004	-503
MX (N.mm)	-94329000	95346000
MY (N.mm)	-31716000	31692000
MZ (N.mm)	-1.92E+09	1.92E+09

Table E4 – ABAQUS Input, Abnormal Sustained

	Abnormal Sustained Loadcase
Loading Factor at Instability	1.76
TD/12 Factor	0.9
Limiting Loading Factor	1.58

Table E5 – Limit Load Assessment – Abnormal Sustained

[redacted]

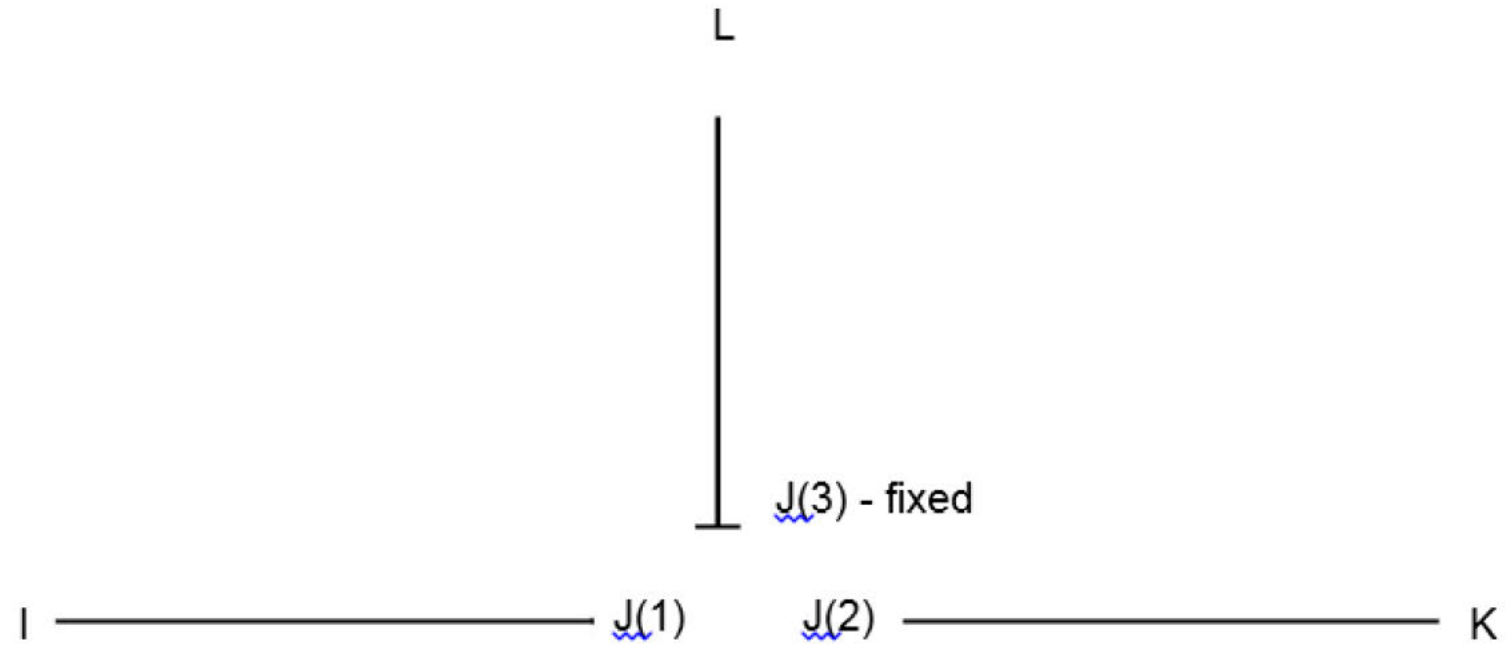


Figure E1 - Beam Schematic

[redacted]

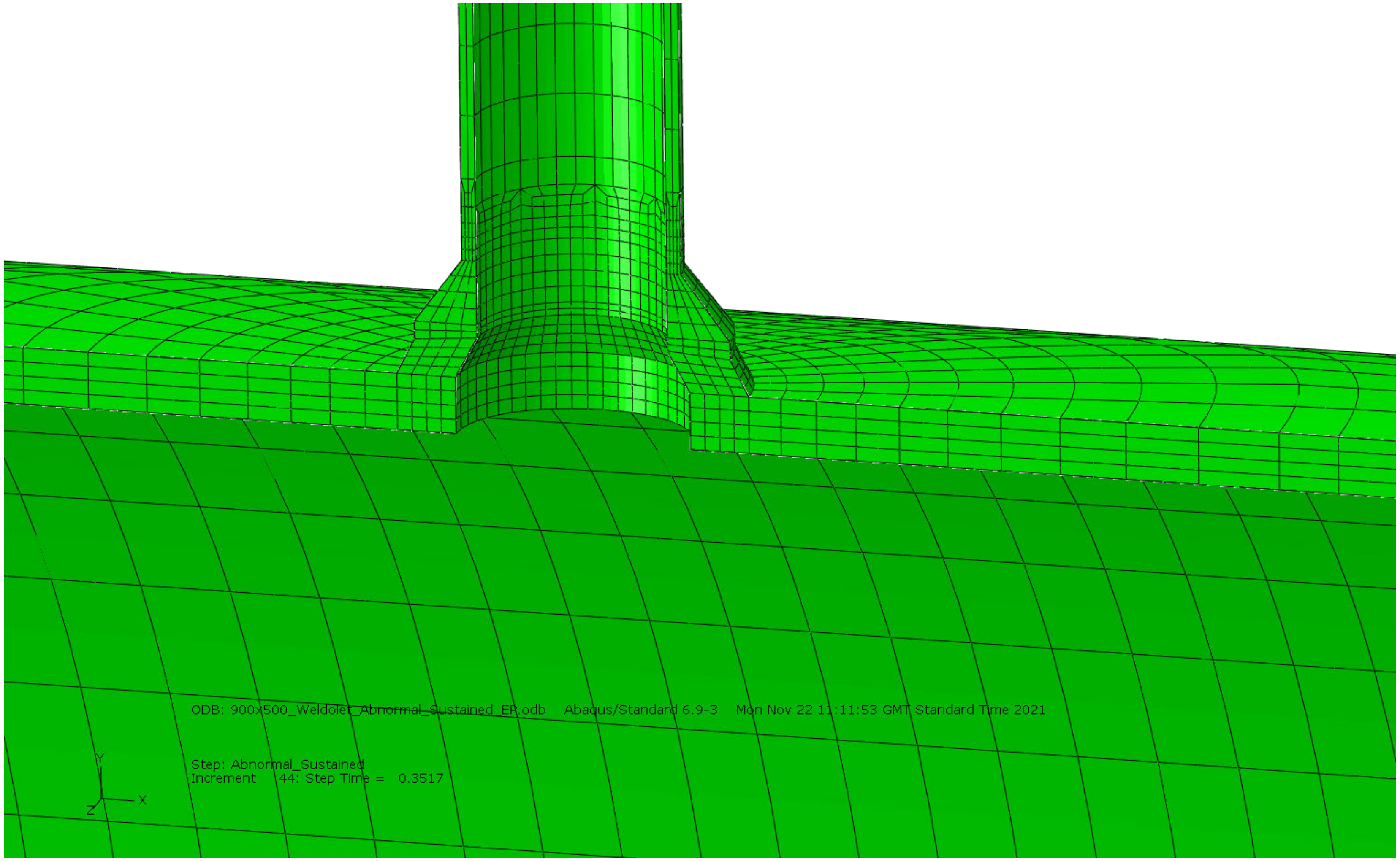


Figure E2 – 900mm x 50mm Weldolet Mesh

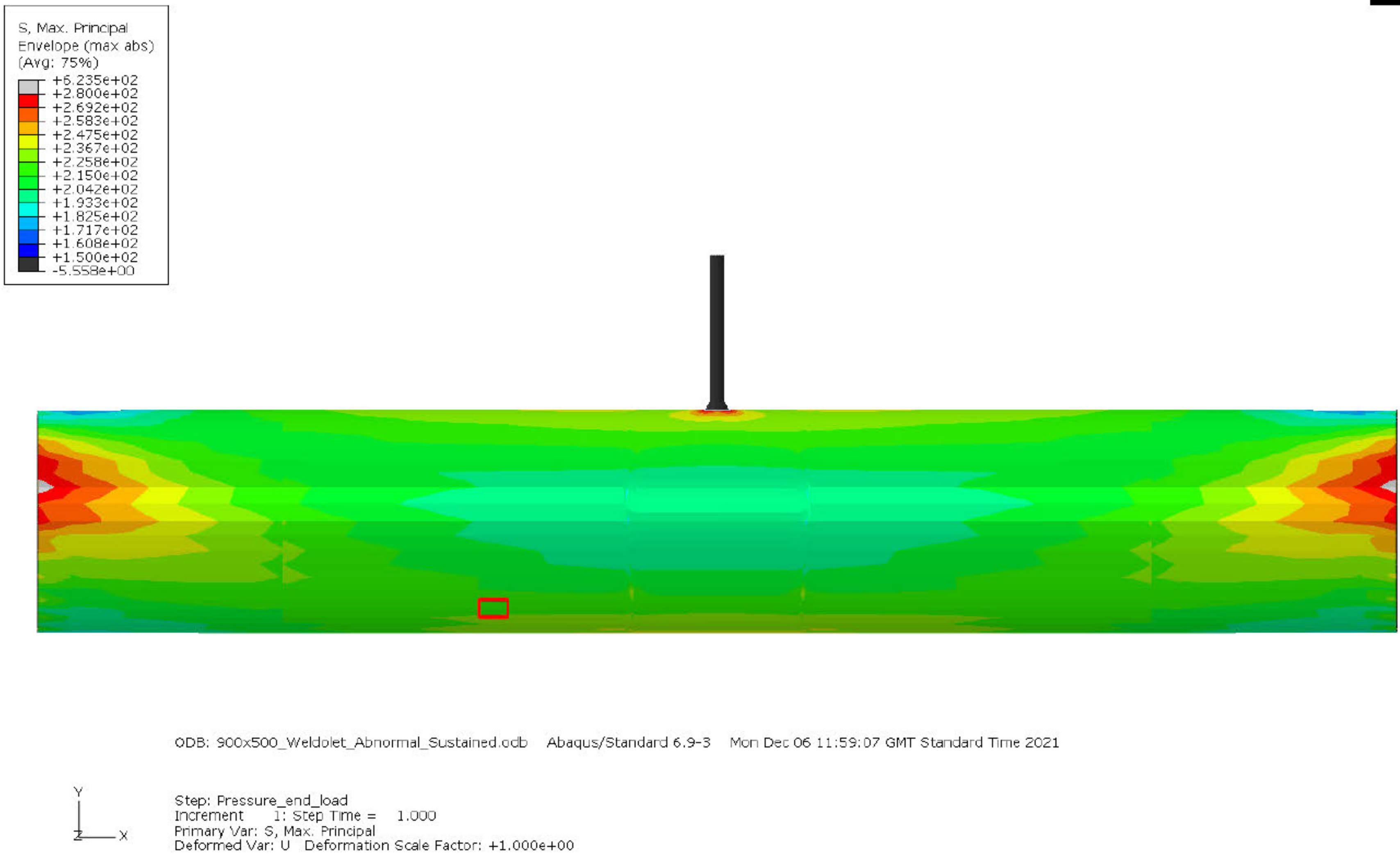


Figure E3 – Max. Principal Stress Due to 79.5 barg

[redacted]

APPENDIX F 50MM X 50MM TEE ASSESSMENT

F.1 GEOMETRY

In the absence of specific geometrical data the geometry of the tee is assumed to meet the requirements of the 1993 edition of T2. The properties used are shown in Table F1.

F.2 FINITE ELEMENT MODEL

The three-dimensional finite element (FE) model of the tee was constructed using MSC Patran and analysed using the general purpose FE code ABAQUS. Twenty-noded, three degree of freedom reduced integration brick (hexahedral) elements, C3D20R, were used for the analysis.

Beam elements representing the pipe stress model are tied to the open ends of the 3D solid model using rigid multi-point constraints (MPCs), as shown schematically in Figure F1. The three nodes J(1), J(2) and J(3) are coincident at the intersection but are not connected. The branch node, J(3), is fixed by a translational and rotational boundary condition, whilst forces and moments are applied at the header nodes J(1) and J(2).

The beams allow the application of forces and moments from the pipe stress model onto the solid model of the fitting. Adequate lengths of header and branch pipe are modelled such that the local effects of the MPCs are removed from the area of interest at the fitting.

The FE mesh created for the 50mmx50mm tee is shown in Figure F2.

F.3 MATERIAL PROPERTIES

Young's modulus and Poisson's ratio equal to 210000 N/mm^2 and 0.3, respectively, were used in all analyses. The actual material grade of the tee is unknown and has therefore been modelled assuming minimum required mechanical properties as per T2 1993. Grade B material grade has been assumed which has a SMYS of 241MPa and SMUTS of 413MPa.

Material property details for the tee and matching header and branch are provided in Table F1.

F.4 LOADS

F.4.1 **Internal Pressure**

Distributed pressure loads were applied to all internal surfaces.

In order to represent the branch and one of the header sections being 'capped off' downstream of the fitting, pressure end loads were applied to the header pipe

[redacted]

elements via the MPCs. The branch pressure end load was taken into consideration by the reaction at the branch boundary condition.

F.4.2 System Forces and Moments

For the assessment criteria considered, forces and moments were extracted for the most highly stressed fitting only, details of the IGE/TD/12 assessments considered and associated loadcase from the pipe stress analysis are provided in Table F2.

Before application to the FE model, the extracted forces and moments were converted to the axis convention of the FE model.

The extracted forces and moments are given in Table F3 and the forces and moments applied to the FE model are given in Table F4.

F.5 ANALYSIS

The assessment of the 900mmx900mm tee, of Appendix A, indicated very high stresses in the fitting which exceeded the linear elastic assessment criteria of IGE/TD/12, for both plastic collapse and shakedown. For this reason, and in order to obtain a more accurate solution, non-linear analyses have been undertaken to determine the acceptability of the 50mmx50mm tee.

F.5.1 Plastic Collapse (Limit Load Analysis)

Protection against plastic collapse is demonstrated by undertaking an elastic-perfectly-plastic (limit load) analysis to determine the load which causes overall structural instability.

F.6 RESULTS

F.6.1 Internal Pressure

A contour plot of maximum principal stresses due to an internal pressure loading of 79.5 barg is presented in Figure F3. Away from concentrations, maximum principal stress in the adjoining pipe is in the range 30 to 40 MPa. Classical theory predicts a hoop stress of 43.3 MPa in the outside wall for a wall thickness of 5.54mm. This provides some confidence in the model.

F.6.2 Sustained

F.6.2.8 Limit Load Analysis

Owing to the complex geometry of the tee, and to eliminate the ambiguity of selecting suitable planes for linearsation across a section, a limit load analysis has been performed in accordance with Section A6.7 of TD/12.

Table F5 summarises the results of the assessment, a limiting loading factor of 3.21 was found for the abnormal sustained loadcase, and therefore the tee is fit for purpose for the anticipated abnormal sustained loadings.

[redacted]

F.7 CONCLUSIONS

1. A three-dimensional finite element model of the 50mmx50mm tee has been created.

2. System forces and moments, giving rise to the sustained and shakedown exceptions have been extracted from the relevant pipe stress model and applied on the FE model together with internal pressure.

3. Finite element analysis of the 50mmx50mm tee has been undertaken using the ABAQUS software, with a subsequent limit load assessment to the TD/12 DBA criterion for sustained loading.

4. In lieu of a TD/12 elastic-plastic shakedown criterion, an incremental plastic collapse assessment has been undertaken to the requirements of ASME VIII Division 2.

5. The stresses in the 50mmx50mm tee have been shown to be less than the TD/12 DBA criteria for plastic collapse.

6. The 50mmx50mm tee has been shown to satisfy the elastic-plastic incremental plastic collapse criterion of ASME VIII Div 2.

[redacted]

Header Pipe			Branch Pipe			Material Grade	
Diameter	Wall Thickness	Material Grade	Diameter	Wall Thickness	Material Grade	Grade B	
						SMYS	UTS
60.3	5.54	B	60.3	5.54	B	241	413

Table F1 –50mm x 50mm Tee Details

Assessment	Reported Code Stress Ratio (%)	Usage	Model Name	Node Number
Abnormal Sustained	141.84	-	KL_CLAY_SETTLEMENT_FF_01	16980

Table F2 – Loadcases Assessed

[redacted]

Node	fx(N)	fy (N)	fz (N)	mx (N.m)	my (N.m)	mz (N.m)
16970	1639	14315	-60	45	35	1207
16980	-1639	-14310	60	-45	-39	-2116
18370	-1639	-14301	60	-41	-39	-2012
16980	1639	14306	-60	45	39	2116
16980	0	5	0	0	0	0
18380	0	0	0	0	0	0

Table F3 – Abnormal Sustained Extracted Forces and Moments, 900mmx50mm weldolet, Node 6160

Load Type	Value	
	Node 126002	Node 126001
FX (N)	14306	5
FY (N)	-1639	0
FZ (N)	60	0
MX (N.mm)	39000	0
MY (N.mm)	-45000	0
MZ (N.mm)	-2116000	0

Table F4 – ABAQUS Input, Abnormal Sustained

	Abnormal Sustained Loadcase
Loading Factor at Instability	3.57
TD/12 Factor	0.9
Limiting Loading Factor	3.21

Table F5 – Limit Load Assessment – Abnormal Sustained

[redacted]

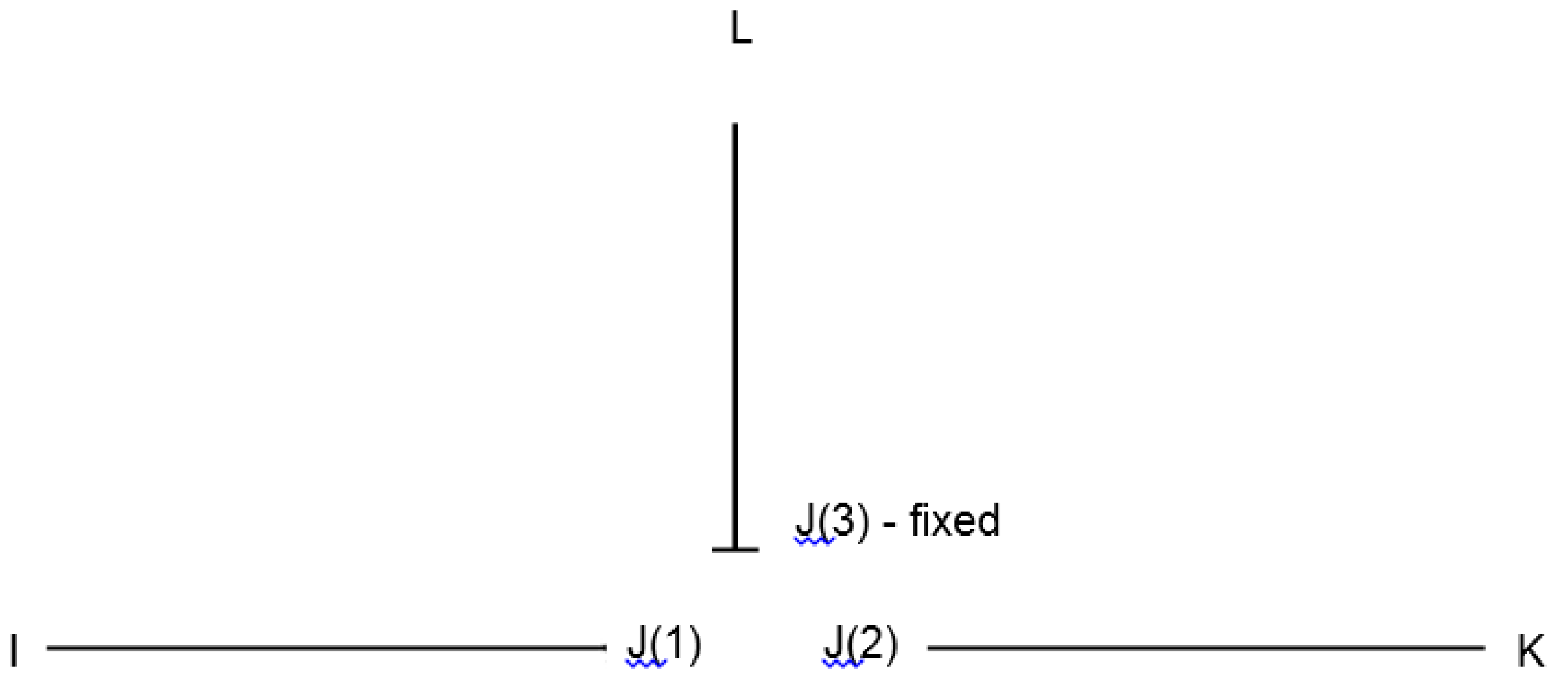


Figure F1 - Beam Schematic

[redacted]

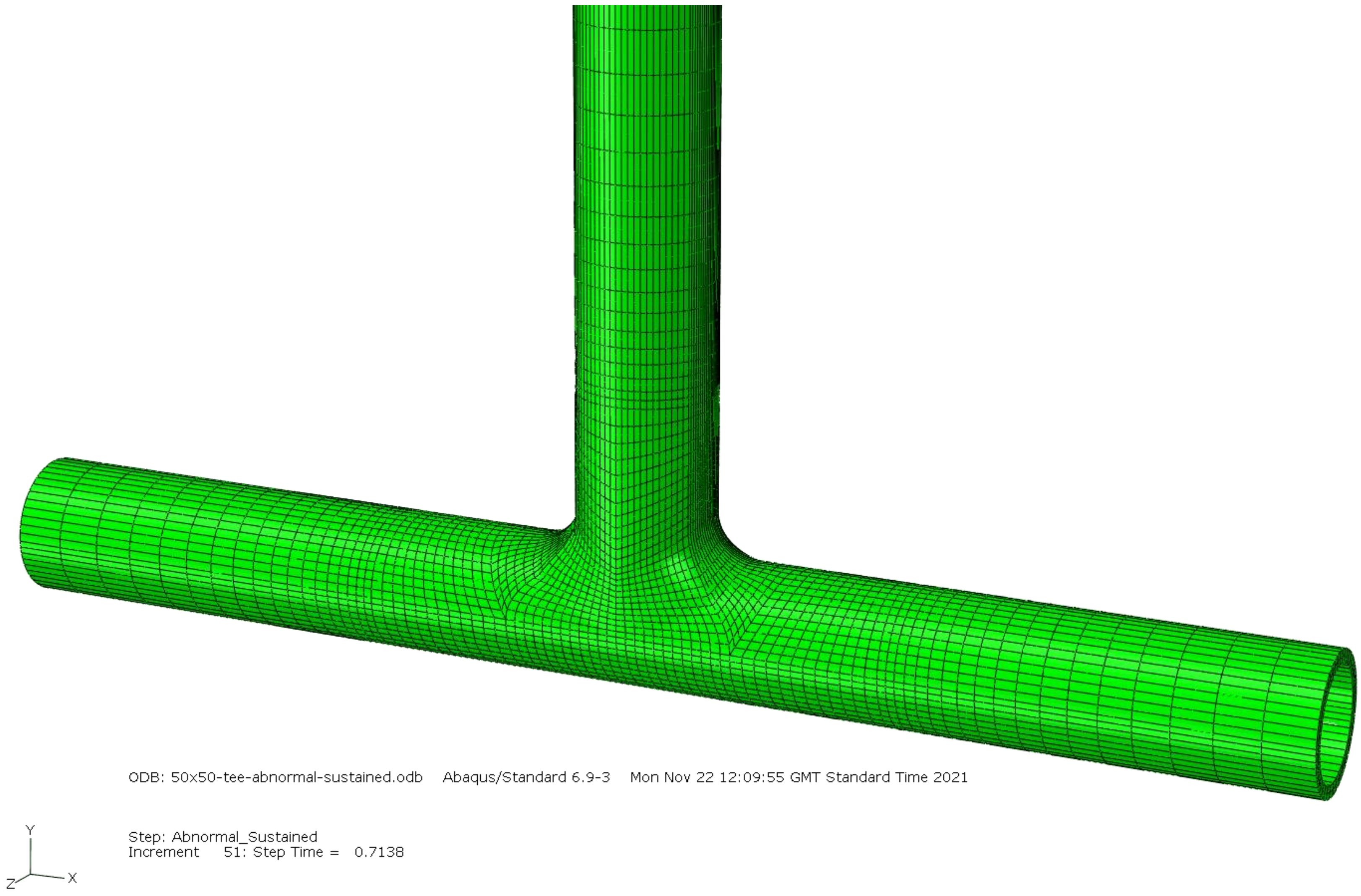
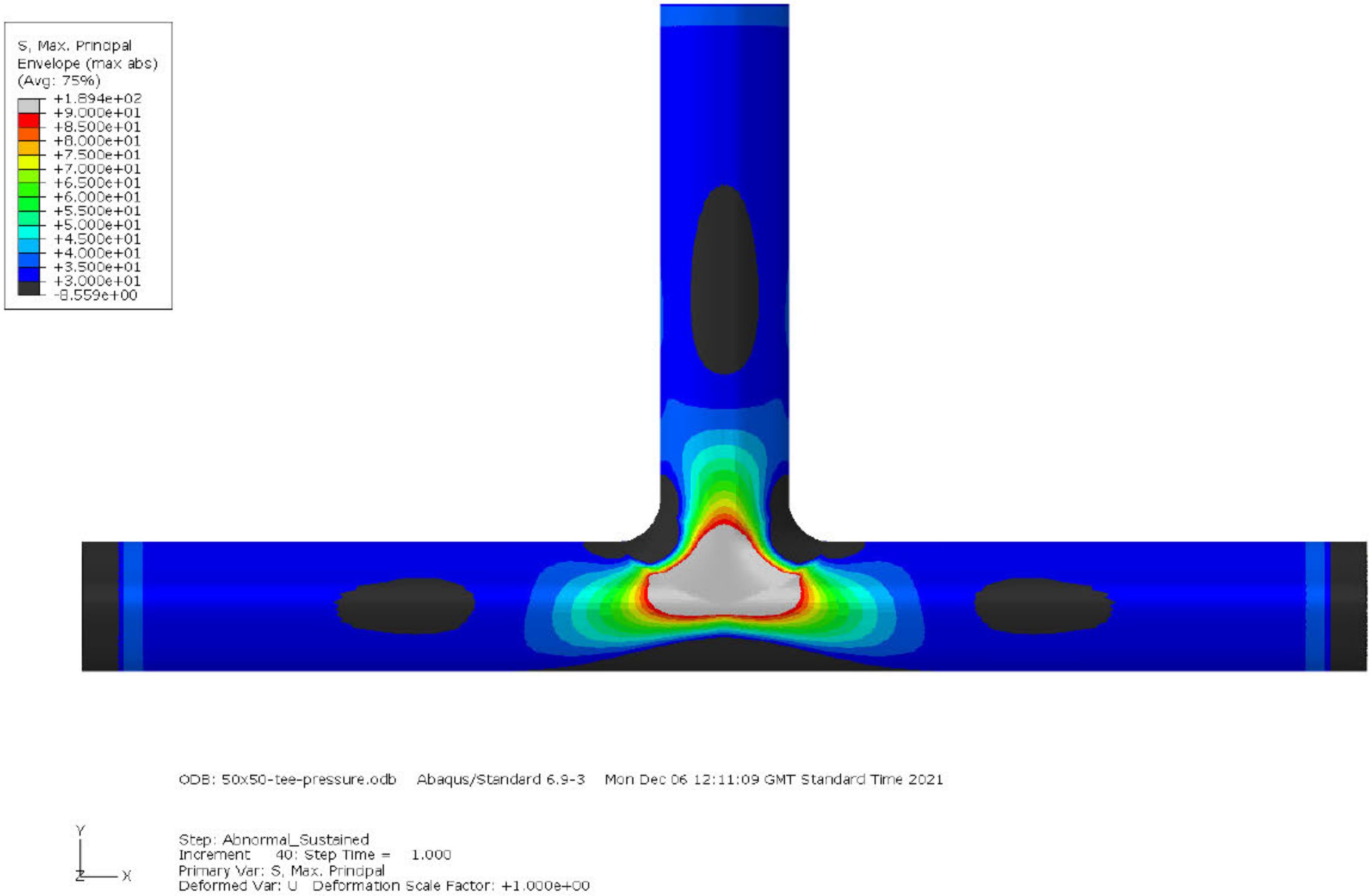


Figure F2 – 50mm x 50mm Tee Mesh



<u>Figure F3 – Max. Principal Stress Due to 79.5 barg</u>