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Strength investigation of the visor side locking device, numerical calculations

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Strength investigation of the visor side locking device, numerical calculations

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Abstract

The structural behaviour of the visor side locking device of MS Estonia was numerically examined. The loading was assumed to be caused by wave pressure distribution acting on the visor shell plating that generates an opening moment to the visor. Load-deflection behaviour was predicted and an estimate of the load carrying capacity of the structure was obtained.

Non-linear elasto-plastic as well as linear elastic analyses were conducted using finite element method (FEM). Both physical and geometrical non-linearities were taken into account in the analyses. A total of three different calculation models were prepared. Firstly, a model describing the undamaged original structure was prepared. Variation of the loading direction was conducted with this model. Secondly, a model with damaged horizontal stringer was prepared. In this model the welding between the stringer and the bulkhead below the lug at some distance was supposed to be detached. The background for this model was the high stress level that was induced into the horizontal stringer at loaded condition. It indicates that the stringer would eventually be teared apart from the bulkhead. Thirdly, a model describing the first experimental test was prepared. The object for this model was to measure the quality of the calculations with experimental results.

The estimated ultimate load for the side locking lug is 1.6 MN. At that load level the plastic deformations in horizontal stringer become so large that the stringer plating below the lug will be teared apart from the bulkhead. After the stringer is detached the load-carrying capacity will be lowered and according to calculations the ultimate load for the damaged structure is about 1.3 MN. If the plane at which the loading force is acting, is rotated towards the side plating, the calculated ultimate load will be lowered.

DISTRIBUTION

The Joint Accident Investigation Comission of Estonia, Finland and Sweden 15 pcs
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CONTENTS

1 INTRODUCTION

The aim of this study was to numerically examine the structural behaviour of the visor side locking device of MS Estonia. The loading was assumed to be caused by wave pressure distribution acting on the visor shell plating. This loading generates in turn an opening moment to the ship's visor [1].

The load-deflection behaviour of the side locking device was predicted and furthermore an estimate of the load carrying capacity of the structure was obtained.

Non-linear elasto-plastic as well as linear elastic analyses were conducted using finite element method (FEM). Both physical and geometrical non-linearities were taken into account in the analyses.

A total of three different calculation models were prepared. Firstly, a model describing the undamaged original structure was prepared. This model was applied to make predictions of the load-carrying capacity of the side locking device. Also variation of the loading direction was conducted with this model.

Secondly, a model with damaged horizontal stringer was prepared. In this model the welding between the stringer and the bulkhead below the lug at some distance was supposed to be damaged. The background for this model was the high stress level that was induced into the horizontal stringer at loaded condition. It indicates that the stringer would eventually be teared apart from the bulkhead plating under the lug. The numerical procedure used in this study is, however, formulated such that this kind of phenomena can not be modelled. So, with the second model the situation at which the stringer is damaged was simulated.

Thirdly, a model describing the first experimental test was prepared. The object for this model was to measure the quality of the calculations with experimental test results.

1.1 Structure and loading

The locking device consisted of a lug that was welded at the bulkhead plating of the visor. The plating below the lug was strengthened with two vertical stringers and a horizontal stringer. The lug was situated unsymmetrically with respect to the beams. The plate thicknesses of the primary structural members were as follows:

- bulkhead 8 mm,
- horizontal stringer 10 mm and
- vertical stringers 20 mm.

The arrangement of the lug in respect with the stringers is shown in Fig. 1. Fig. 2 shows the dimensions of the lug that were used in the calculations. The drawings prepared by the shipyard did not give clearly the dimensioning of the lug. To estimate the dimensions, manual measurements from the actual visor were made and it was found out that the height of the lug was about 380 mm and width about 60 mm.

The material was modelled with the following mechanical properties:

Young´s modulus: 207 GPa and
Poisson´s ratio: 0.29.

The yield stress and ultimate strength were taken from experimental tension test results (Appendix A) and they were found to be:

for the horizontal stringer:

yield stress:	332 MPa and
ultimate stress in uniaxial tension:	476 MPa,

other members excluding the lug and weld:

yield stress:	306 MPa and
ultimate stress in uniaxial tension:	454 MPa.

In the calculations elasto-plastic material model that uses the von Mises yield surface was used. The stress-strain curve consisting of three linear parts (Figs. 3a and b) was applied to describe the non-linear material behaviour. The material model makes the assumption that after 18 % strain the material is perfectly plastic which means that further straining does not induce higher stress in the material.

The lug as well as the welds were modelled to have pure linear-elastic material behaviour.

The force acting on the locking device was thought to be induced by the opening moment caused by the sea load to the visor. The direction of the loading is shown in Fig. 4.

The following element types were used in the FE-idealization: the lug and the weld were modelled with solid elements. The bulkhead plating, the horizontal stringer beneath the lug and the vertical stringers beneath the lug were modelled with shell elements.

1.2 Analysis programs

A computer aided design package, I-DEAS [2], was used as a pre- and post-processor. In addition, the linear elastic analyses were done with I-DEAS. The non-linear elasto-plastic cases were analyzed with commercial finite element package ABAQUS [3]. Also the post-processing software ABAQUS-POST [4] was used in post-processing the ABAQUS results. Following ABAQUS element types were used in non-linear analyses:

S8R:	shell element (8-noded quadrilateral),
STRI65:	shell element (6-noded triangle),
C3D20:	solid element (20-noded brick),
C3D15:	solid element (15-noded wedge) and
C3DD10:	solid element (10-noded tetrahedra).

The solutions of the non-linear equilibrium equations were obtained by using so called modified RIKS method. This solution algorithm can handle unstable problems where the load or displacement may decrease as the solution evolves.

2 STRENGTH INVESTIGATION OF THE SIDE LOCK

2.1 Numerical models

The finite element discretization is shown in Figs. 5 and 6.

Characteristic sizes of the model were:

- number of elements 907,
- number of nodes 3019 and
- degrees of freedom 15963.

The FE-model extended up to the side plating in the horizontal direction and in the vertical direction two stringer spaces. The horizontal stringer as well as the vertical stringers below the lug were modelled. Moreover, local plate stiffeners attached to the bulkhead as well as to the horizontal stringer plating were modelled.

Fixed boundary conditions were used at the model edges as shown in Fig. 7.

The load was applied as nodal forces acting on the inner surface of the lug's attachment hole.

2.2 Results

In the analysis run displacement and also stress and strain state were calculated and stored at selected load increment steps. The solution procedure calculates the stresses and the strains at so called integration points which are located inside the elements. These integration point values were then extrapolated to element nodes and furthermore to the element mid-plane using element's shape functions. The extrapolation was done by the analysis program.

In the analysis five integration points through the element thickness were used.

Only the membrane values (i.e., values that are calculated at the element mid-plane) are considered.

2.2.1 Undamaged structure

The calculated results are shown in Appendix B and they consist of:

- load-displacement curve of one loaded point of the lug,
- structure's deformed shape at the last calculation step,
- von Mises stresses at the horizontal stringer,
- membrane stresses at the horizontal stringer,
- von Mises strains at the horizontal stringer,
- membrane strains at the horizontal stringer,
- von Mises stresses at the bulkhead,
- von Mises strains at the bulkhead,
- equivalent plastic strain at the horizontal stringer and
- equivalent plastic strain at the bulkhead.

The analysis-run consisted of a total of 74 load increments and was then terminated because the load increment was becoming very small. At that point the load level was 1.63 MN. The calculated load-deflection curve for one loaded point at the lug measured in the loading direction is shown in Appendix B. According to the curve the maximum displacement in the load's direction is about 3.5 mm. In the figure the curve is extrapolated linearly up to 5 mm's displacement and the load obtained at that point is about 1.9 MN. Due to the plastic deformation the stiffness of the structure is gradually decreasing. At the load level of 1.63 MN the stiffness is approximately 20 % of the structure's original stiffness. (Here the stiffness of the structure is defined as the tangent of the load-deflection curve.)

In Appendix B also the equivalent plastic strain at the horizontal stringer is shown. At the load level of 1.37 MN a narrow strip just below the lug has become plastic. As the loading increases, the plastic region increases also and finally at the load level of 1.63 MN another continuous plastic region below the lug is formed. It is interesting to note that at that load level the membrane stress distribution at the stringer also shows a continuous high stress region below the lug. This indicates that it is quite possible for the horizontal stringer material to be teared apart from the bulkhead plating by the lug.

By integrating the stress distributions in stringer and bulkhead the resulting forces acting in these members were calculated. They were found to be when the loading is about 1.6 MN:

- horizontal stringer: 0.56 MN
- bulkhead plating: 0.63 MN + 0.36 MN + 0.04 MN + 0.01 MN= 1.07 MN

2.2.2 Structure with damaged stringer

In this model the horizontal stringer was detached from the bulkhead plating between the vertical stringers (about 130 mm) and moreover the vertical stringers were detached from the bulkhead by a distance of 30 mm.

The calculated results are shown in Appendix C. The corresponding results as in Appendix B are shown.

The analysis-run consisted of a total of 69 load increments. At the last calculation point the load level was 0.94 MN. The calculated load-deflection curve for one loaded point at the lug measured in the loading direction is shown in Appendix C. According to the curve the maximum displacement in the load's direction is about 2.9 mm. In the figure the curve is extrapolated linearly up to 5 mm's displacement and the load obtained at that point is about 1.3 MN. At the load level of 0.94 MN the stiffness is approximately 37 % of the structure's original stiffness.

2.2.3 Variation of the loading direction

The effect of the loading direction was studied with two different load cases. As the loading was in the previously described case acting in a plane parallel with the ship's centre plane, now the loading was rotated towards the side plating to have angles of 30° and 60° between the loading plane and the ship's centre plane. The angle between the horizontal plane and the loading plane was however the same as in the previous case.

The calculated results for the two cases are shown in Appendix D.

The analysis-run consisted of a total of 50 load increments. At the last calculation point the load level was 1.26 MN when load was acting on 30° angle and only 0.43 MN when load was acting on 60°. The maximum displacement in the load's direction is about 14 mm and 16 mm respectively. The stiffness at the last calculation point is approximately 34 % when the loading direction is 30° and 28 % when the direction is 60° compared with the structure's original stiffness. A comparison with all the calculated load-deflection curves is shown in Fig. 8.

3 NUMERICAL CALCULATION OF THE TEST

3.1 Numerical model

The test structure consisted of two similar lugs. The finite element model of the analysed structure is shown in Appendix E Figs. 1 and 2. Due to symmetry only one half of the other lug was modelled.

Because the horizontal stringer would eventually buckle as the loading is increased, the modelling of the attachment of the stringer to the vertical bulkhead as well as to the side plate and also to the vertical stringers was important. In the calculation model the horizontal stringer was attached to the bulkhead all along its length. Moreover, the stringer was attached to the side plating in 87 mm's distance according to Fig. 2 in Appendix E.

By using shell elements in the modelling only the mid-plane of the vertical stringers were modelled. To make realistic aspect ratio for the horizontal stringer that would buckle, the thickness of the vertical stringer was taken into account by multi-point constraints (see Fig. 2, Appendix E). The equation for each slave node was of the form:

$$u_{ys} = u_{ym} + \Delta x \cdot \theta_{zm}\text{, where}$$

u_{ys} and u_{ym} are the displacement components in y-axis direction of the slave and master nodes respectively, θ_{zm} is the rotation about z-axis of the master node and Δx is the distance between the slave and the master node.

Fixed boundary conditions at the model edges and symmetrical boundary conditions at the model symmetry plane were used, see Appendix E. Fig. 3.

Characteristic sizes of the model were:

- number of elements 763,
- number of nodes 2654,
- degrees of freedom 14349.

The analysis run consisted of 141 load increments.

In the analysis five integration points through the element thickness were used.

3.2 Results

In Appendix E Fig. 4 the measuring points with measuring directions are shown. Transducer S measured the displacement at the loaded point in the load's direction. S1 measured displacement at the plating at the upper edge of the lug. The direction was perpendicular to the plating. R1, R2, R3, R4, R6, R7, R8 and R9 were strain transducers and the were located at the bulkhead plating above the stringer. The measuring direction was the stringer's plane. R5 and R10 were also strain transducers. In the figure strain transducers R6, R7, R8 and R9 are not shown but they measured at the corresponding locations as the transducers R1, R2, R3, R4, respectively, but were located at the plating near the other lug.

In Appendix E Fig. 5 the calculated displacement at the loaded point in load's direction is compared with the measured data. It can be seen that calculation model was somewhat stiffer than the measuring set-up. In the calculations the vertical stringer buckled at about 810 kN's load. The buckled stringer is shown in Appendix E Fig. 12. After buckling the load required to increase the displacement was lower but as displacement increased the required loading was also increasing and the calculation terminated at the loading level of about 880 kN. The displacement of the loaded point at the buckling point was about 8 mm and at the final calculation point about 34 mm. Figure 13 in Appendix E shows the distribution of the equivalent plastic strain at the last calculation step.

In Appendix E Fig 6 the calculated and measured values for the displacement transducer S1 are shown. At that point the linear-elastic stiffness is the same for both cases but the measured structure shows earlier softening behaviour. At load around 790 kN the transducer reached it measuring range and was thereafter not active. The displacement was then about 20 mm. The calculated displacement reached about 43 mm.

In Appendix E Figs 7 and 8 the calculated strain near the weld above the horizontal stringer is compared with measured values of R1 ... R4 and in Figs 9 and 10 the same values are compared with measured values of R6 ... R9. In Fig. 11 the measured values of R5 and R10 are compared with the calculated values.

In the measurements it was found that at the load level of about 300 kN the strain transducers R5 and R10 showed small permanent deformation in the structure. Visually clear deformations were observed at around 600 kN. At load around 850 - 900 kN the structure finally collapsed.

4 CONCLUSIONS

The estimated ultimate load is about 1.6 MN. At that load level the plastic deformations in horizontal stringer become so big that the stringer plating below the lug will be teared apart from the bulkhead. After the stringer is teared apart the load-carrying capacity will be lowered and according to calculations the ultimate load for the damaged structure is about 1.3 MN.

In the case when the load vector does not lie in a plane parallel with ship's centre plane, the load required to cause excessive yielding to the structure is lowered dramatically. When the load vector is offset an angle of 30°, the estimated ultimate load is 1.3 MN and when the load vector is offset by an angle of 60°, the ultimate load is 0.43 MN. When considering these values, it should be kept in mind, that in the modelling the lug was free to move sideways. In reality the locking arrangement would create supporting forces that would restrain the sideways movement of the lug.

In the FE-modelling various idealizations were made. These idealizations came mainly from the analysis effectiveness requirements. Non-linear analysis is usually time consuming especially in the solution stage. Also the required disk storage space increases rapidly as the model size increases. For these reason's idealizations are inevitable. In this analysis the modelling practice where the bulkhead plating as well as the stringers are modelled with shell elements is based on two factors: firstly, the aim of this study was to calculate the force distribution in the structure ignoring very local effects. Secondly, as it became evident that membrane stress distribution in the horizontal stringer is the most important factor, the choice of shell elements seemed to be adequate.

To verify the applicability of the used modelling practice, experimental test was conducted. The calculated ultimate load was about 850 kN and measured ultimate load around 900 kN. The horizontal stringer buckled at around 800 kN. This kind of buckling was also detected in the test structure. On the other hand, it should be noted that buckling of the horizontal stringer was not detected in real visor structure.

The buckling phenomena in the test structure caused some special requirements to the corresponding calculation model. These were as follows: a) the welding to the side plating was critical and in the model the extent of this weld must be taken into account and b) the thickness effect of the vertical stringer showed some effect on the buckling load and was taken into account with constraint equations. These modelling practises were not applied in the calculation model of the ship's visor because no buckling occurred there.

The measured and calculated displacement-load curves agreed quite well. The calculation model was somewhat stiffer as was expected.

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3. ABAQUS, Version 5.5, Hibbit, Karlsson & Sorensen, Inc.

4. ABAQUS-POST, Version 5.5, Hibbit, Karlsson & Sorensen, Inc.

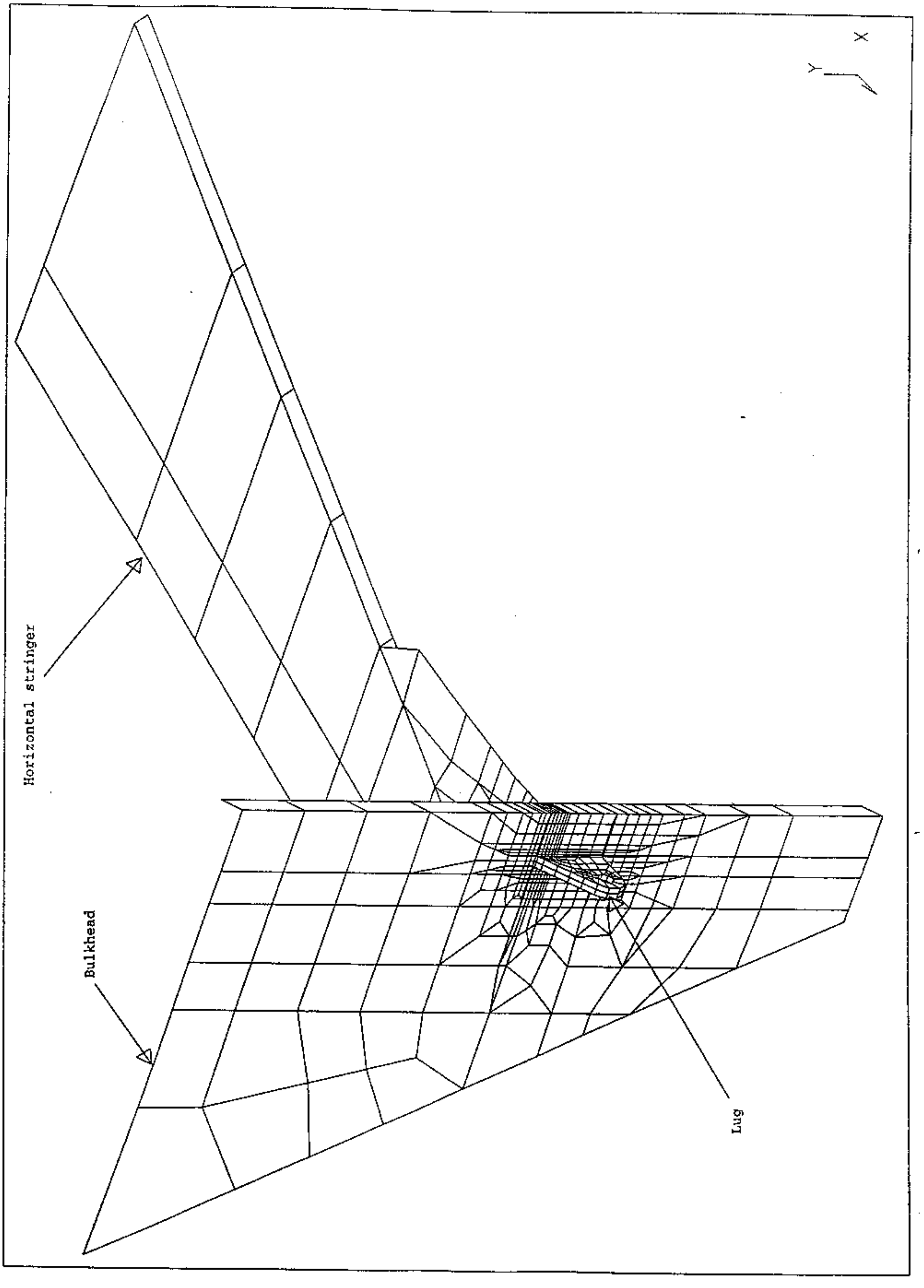


Figure 5. FE idealization

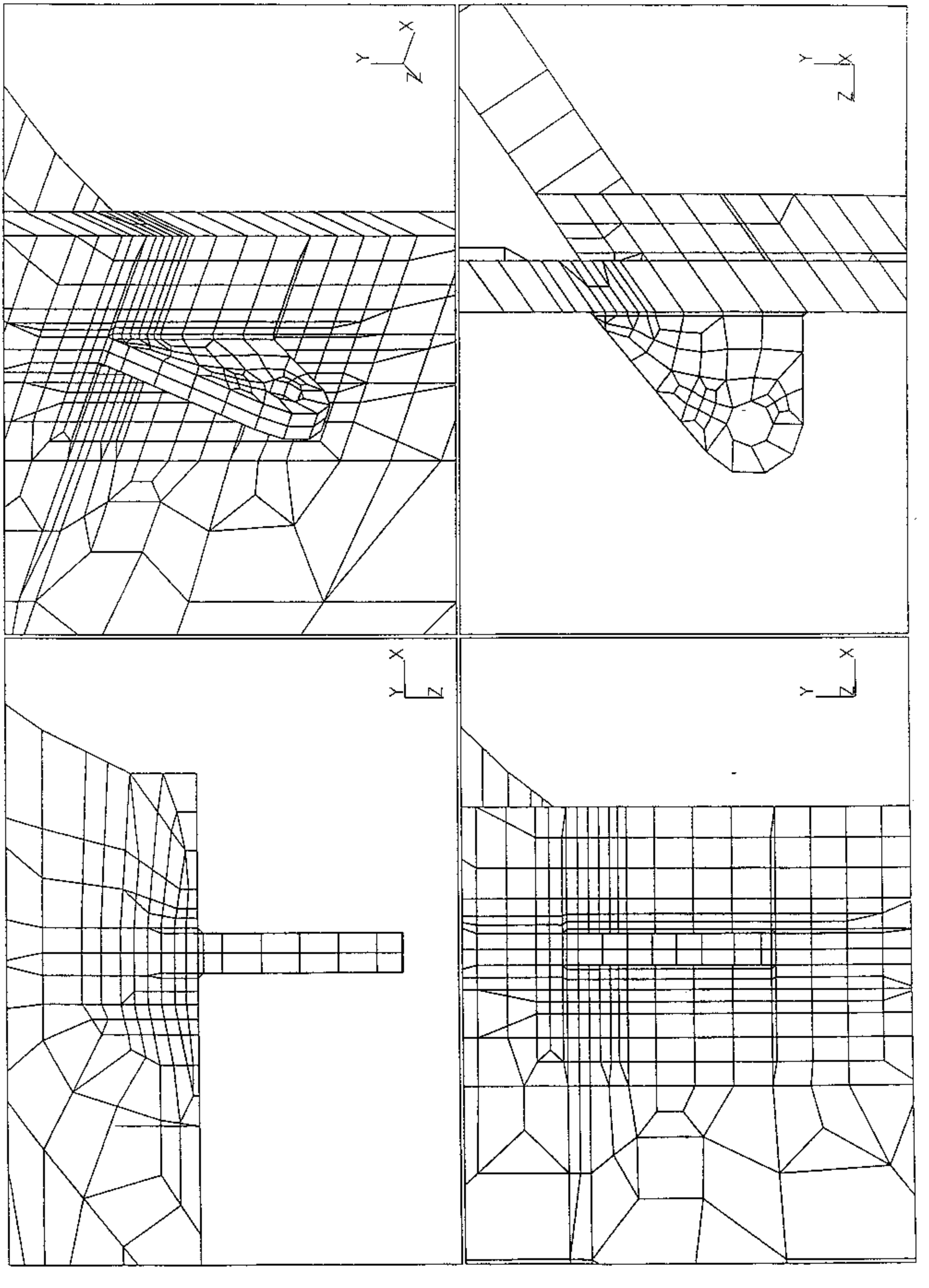
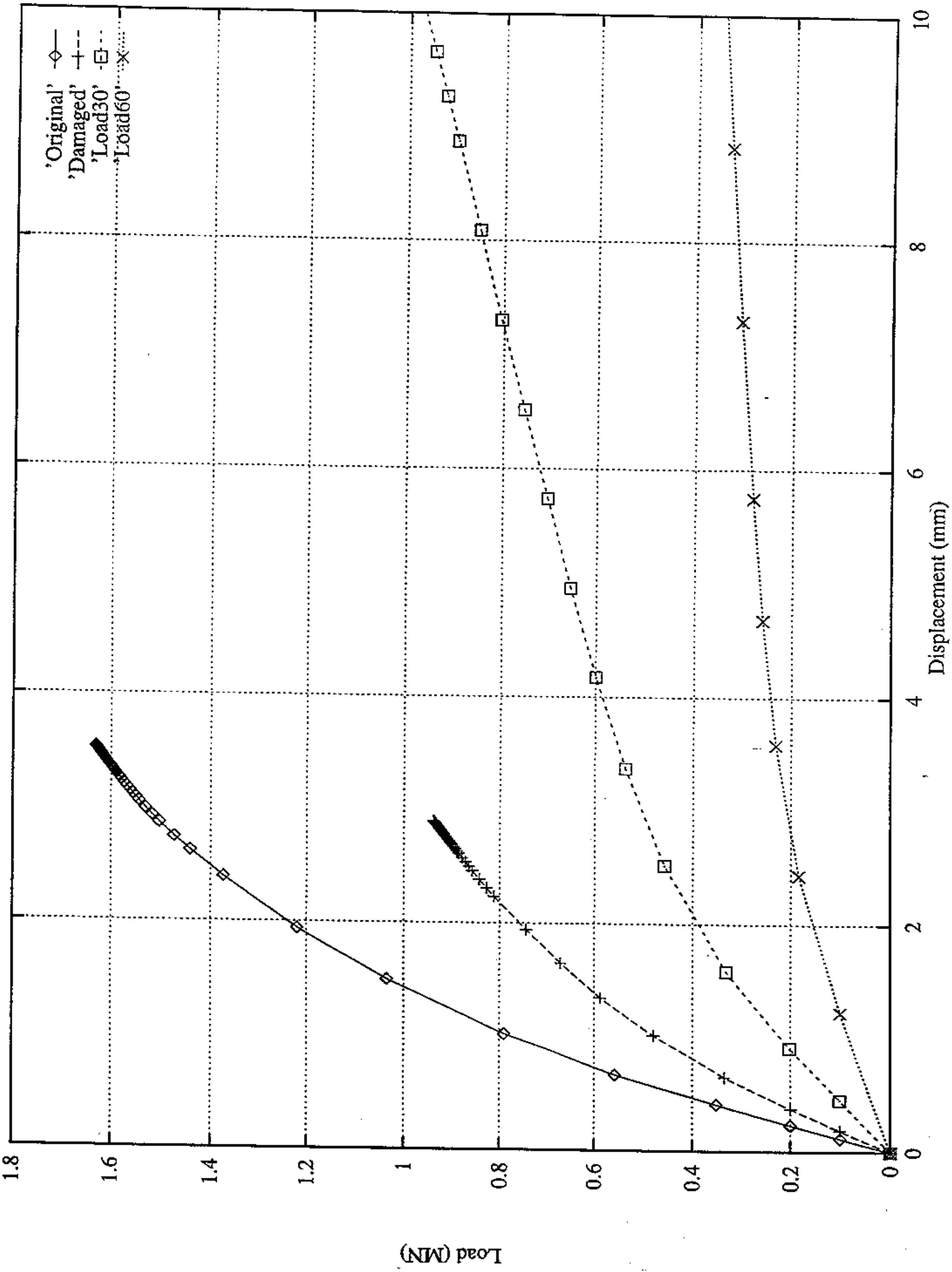


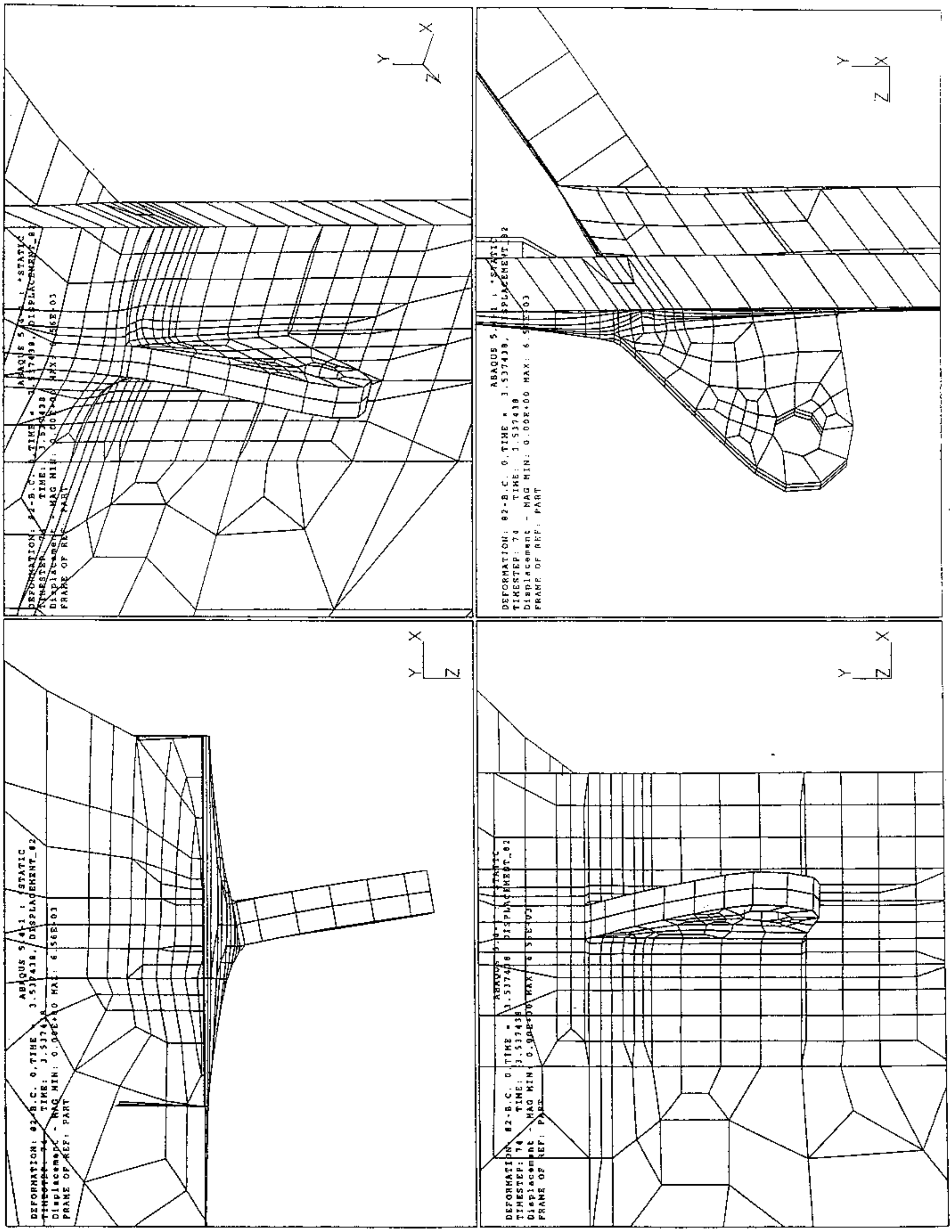
Figure 6. Finite element model of the side lock.

Figure 8. Calculated load-deflection curves.



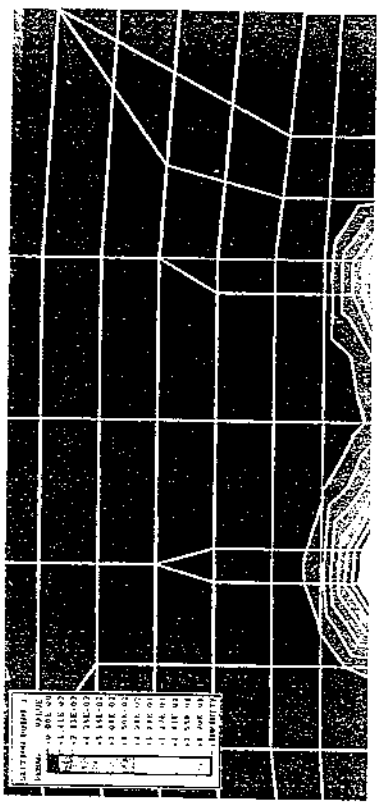
APPENDIX B

Deformed shape at 1.63 MN

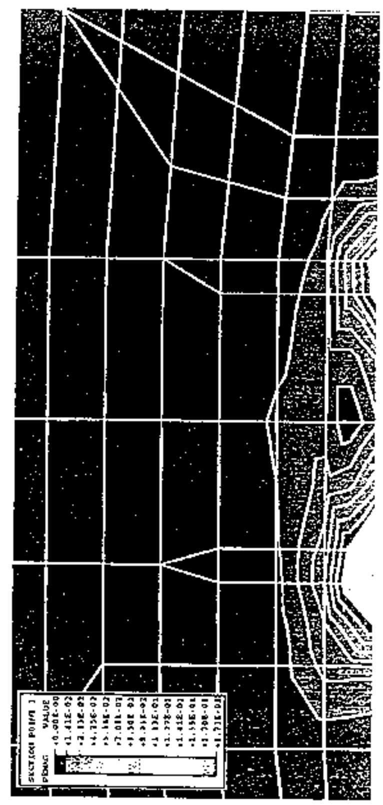


APPENDIX B

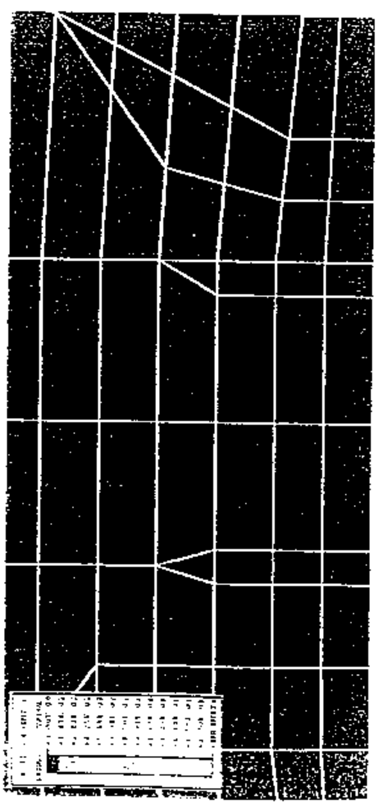
Equivalent plastic strain at the horizontal stringer with load values of 0.56, 1.37, 1.52 and 1.63 MN



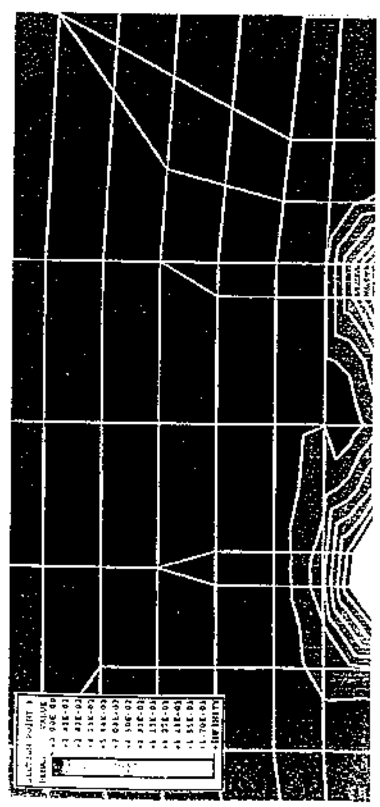
Load 1.37 MN



Load 1.63 MN



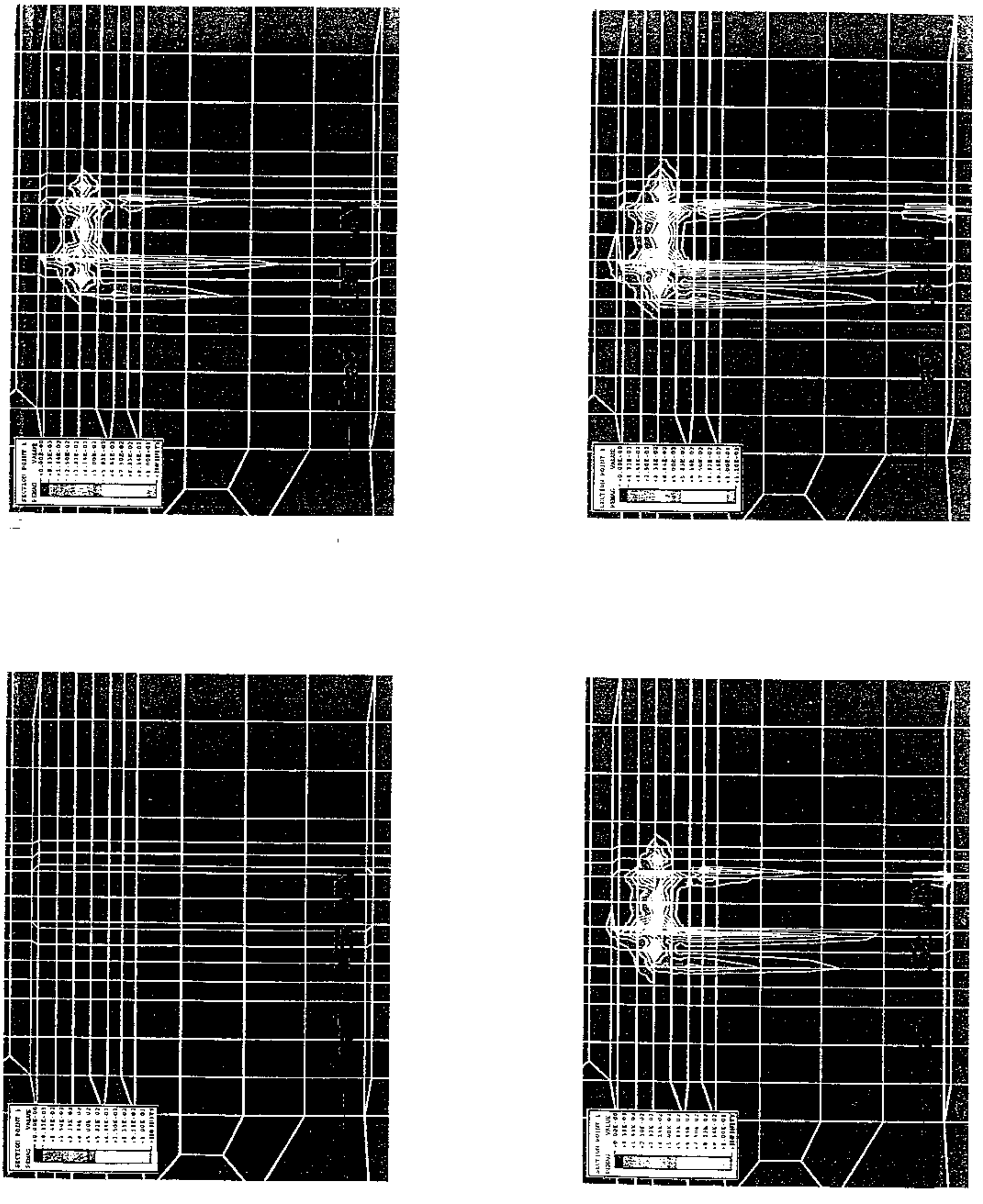
Load 0.56 MN



Load 1.52 MN

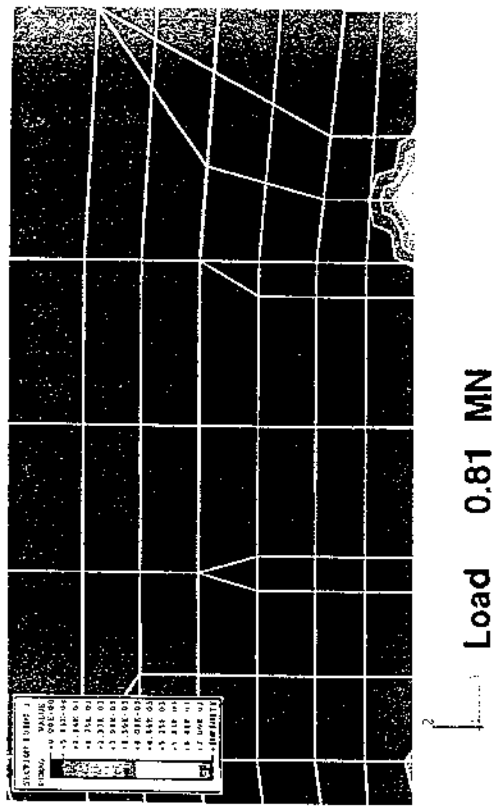
APPENDIX B

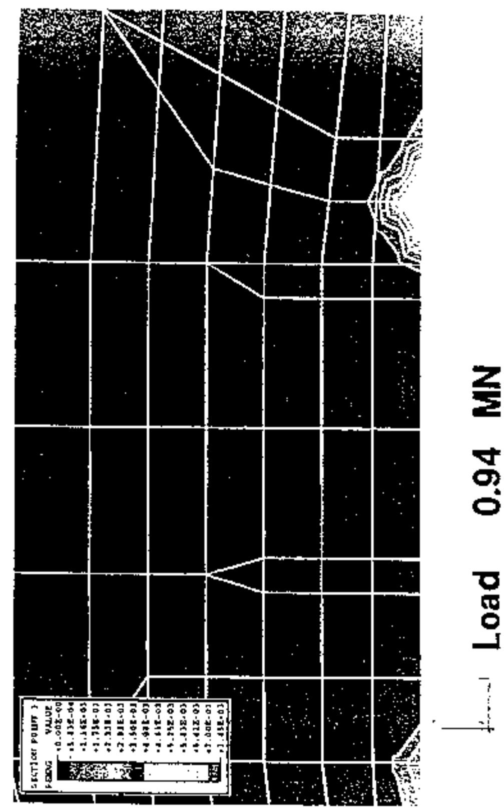
Equivalent plastic strain at the bulkhead with load values of 0.56, 1.37, 1.52 and 1.63 MN

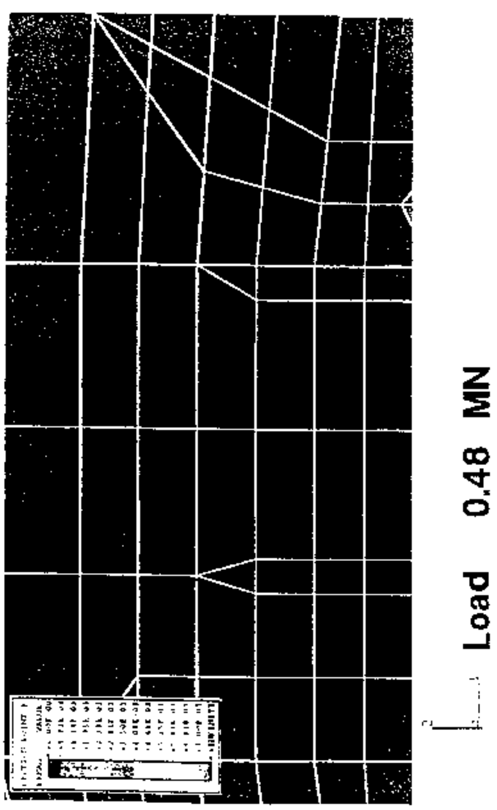


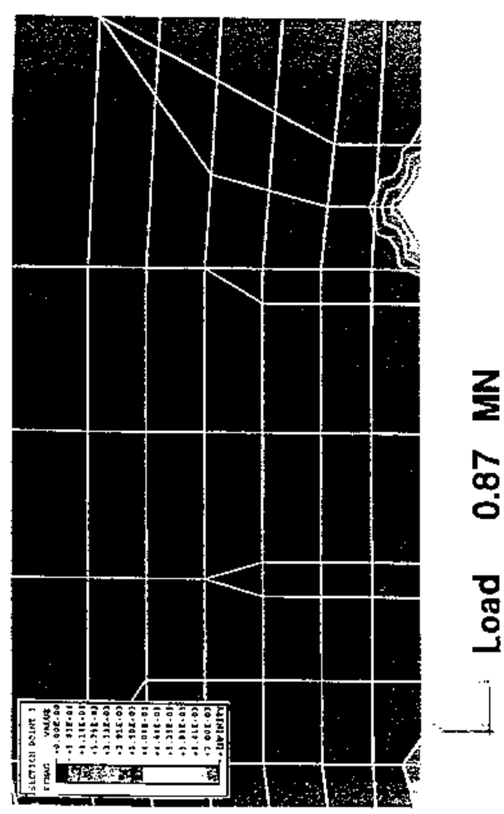
APPENDIX C

Equivalent plastic strain at the horiz. stringer (damaged) with load values of 0.48, 0.81, 0.87 and 0.94 MN



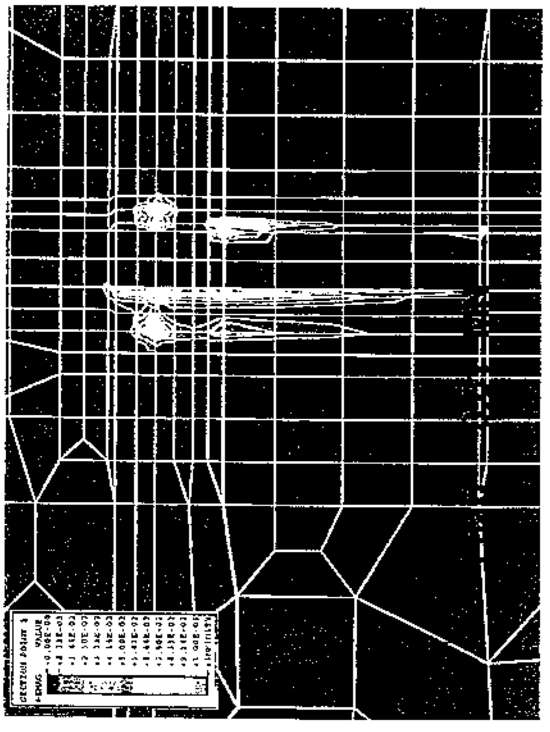


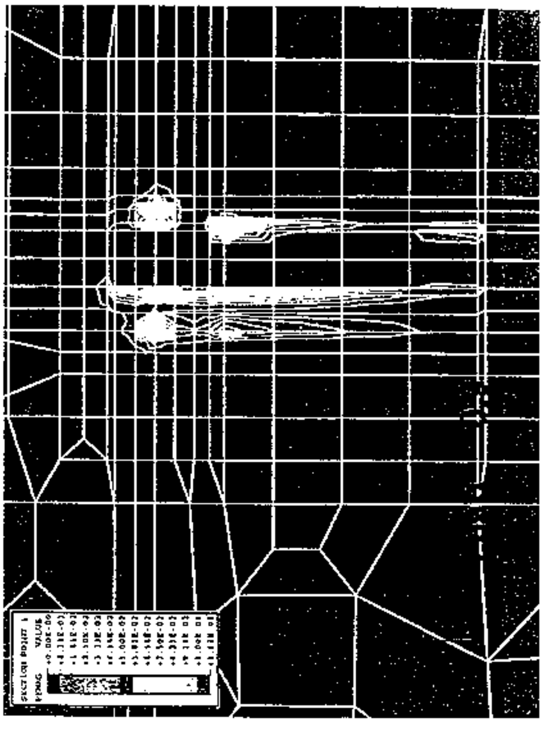


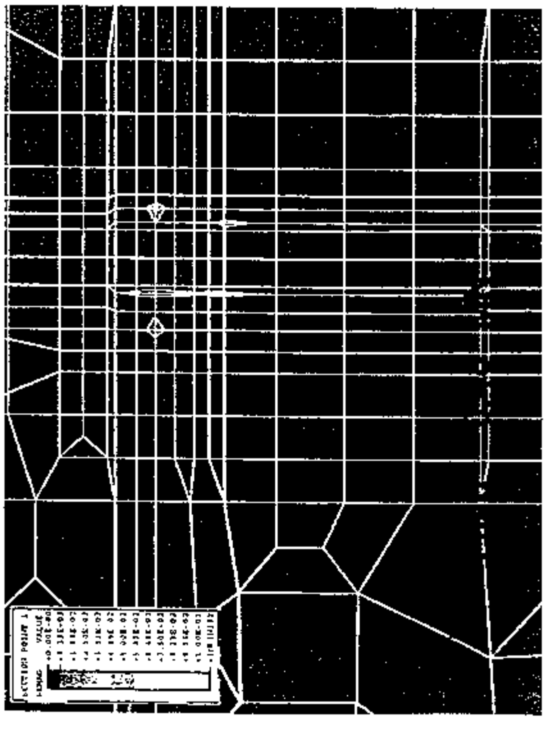


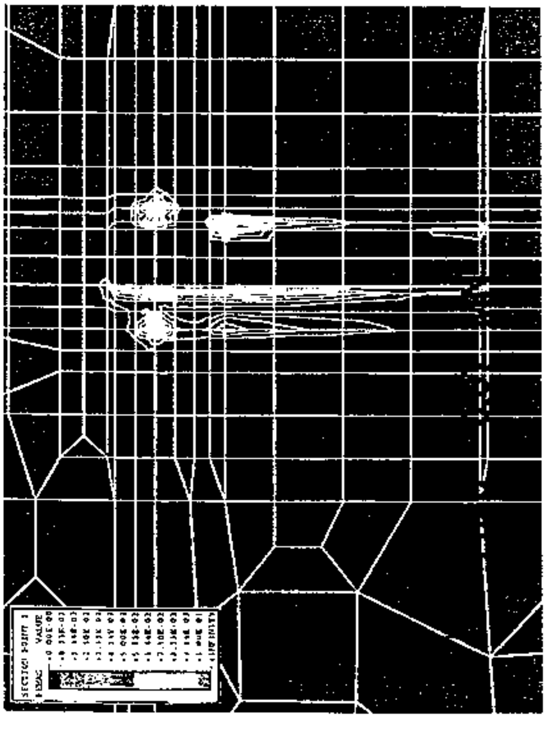
APPENDIX C

Equivalent plastic strain at the bulkhead with load values of 0.48, 0.81, 0.87 and 0.94 MN (damaged)









APPENDIX E

Fig. 8. Strain for points R2 and R4.