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Finite element analysis of the effect of pit shape on the local stress and strain distribution

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ABSTRACT

Previously a finite element analysis had been carried out of the stress and strain distribution associated with a single corrosion pit of both hemispherical and bullet-shaped geometry in a cylindrical specimen of a low alloy turbine disc steel stressed remotely in tension. Recent evidence had shown that 12Cr steam turbine blade steels in simulated condensate environments tended to have pit geometries that were better described as a truncated sphere with depth greater than the radius. Finite element analysis of this geometry was undertaken and the associated stress and strain distribution compared with that for a hemispherical pit of the same depth. The results confirmed the intuitive prediction that for high applied stresses the plastic strain would be even more concentrated near the pit mouth by comparison to the hemispherical pit.

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Approved on behalf of the Managing Director, NPL,
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1 INTRODUCTION

In many applications stress corrosion cracks emanate from corrosion pits. A recent advance has been to demonstrate, through 3D imaging using X-ray tomography (XRT), that cracks may initiate from the pit very near or at the pit mouth¹, though caution was urged in not generalising this observation. There are a number of possible factors that could have been invoked to explain the position sensitivity of crack nucleation, including electrochemical and local topographical features in the pit. However, the evidence for these was not especially apparent. In contrast, detailed finite element (FE) analysis had demonstrated that, for high applied stress, localised plastic strain concentrated near the pit mouth². A novel perspective was to show that a growing pit in a static stress field would create a local *dynamic* plastic strain close to the pit mouth that could be the key factor in crack initiation³.

That analysis was applied to a steam turbine disc steel to complement the detailed stress corrosion cracking and XRT studies of that steel. More recent research has focused on a 12Cr steam turbine blade steel in simulated steam condensate solution and the role of pits in originating fatigue cracks. In this case the observation was that the pit geometry, at least in the size range of interest, was better described by a truncated sphere with a depth greater than the radius, (Figure 1), rather than a hemisphere⁴.

Nevertheless, for this case also, the fatigue crack appeared to initiate near the mouth or sides of the pit as evidenced by the oxidised state of the surface associated with the non-propagating crack when the specimen was first cyclically loaded close to the fatigue limit. The question then posed and addressed in this report is the extent to which strain is more or less localised in this pit geometry by comparison to the hemispherical geometry analysed previously.

2 MATERIAL PROPERTIES AND STRESS CONDITIONS

The mechanical properties appropriate to this analysis for a typical blade steel, FV566, steel are given in Table 1. The test temperature reflects the temperature of the early condensate on a low pressure steam turbine.

Table 1 Mechanical properties (mean values) of the FV566 steel

Condition	T (°C)	E (GPa)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	Elongation (%)
Stress relieved	90	210	841	937	27

Poisson's ratio for the steel was not measured and a value of 0.3 was adopted.

The analysis makes use of the full stress-strain behaviour of the material and a plot of the data is shown in Figure 2.

3 BASIS OF FINITE ELEMENT ANALYSIS

The FE analysis has been carried out using ABAQUS V6.5-7. A 3-D version of the cylindrical specimen was modelled in the ABAQUS CAE pre-processor (see Reference 2 for more details). A pit was created halfway along the length of the specimen.

The mesh was created using the 3-D elements C3D4, which are 4-node linear tetrahedral elements. The mesh was refined in the region around the pit to enhance the accuracy of stress and strain predictions.

Boundary conditions were applied to the ends of the specimen to ensure specimen alignment during loading. A uniform stress was applied to the surface at one end of the specimen. The von Mises material model was used in the analysis to characterise the elastic-plastic behaviour of the material.

4 SPECIMEN GEOMETRY

The specimen and pit geometry and associated mesh structure are illustrated in Figures 3 and 4. The specimen diameter was 6.4 mm. Calculations were performed for a 100 μm deep pit. For the truncated sphere this corresponded to a pit radius of 65 μm and mouth opening of 110 μm .

5 RESULTS AND DISCUSSION

A 3-D representation of the stress and strain distribution for applied stresses ranging from 90% of the 0.2% proof stress to 10% of the 0.2% proof stress is shown in Figures 5-9. Note that the colour coding has a slightly different scale maximum for each applied stress. As noted previously for a hemispherical pit the strain is always a maximum near the pit mouth at all applied stresses and this is confirmed for the truncated sphere, which shows an even greater tendency for strain concentration. However, in both cases the nature of the strain is different at high and low applied stresses. In the latter, the strain is purely elastic and mirrors the stress localisation as would be expected. At high applied stress the strain has a significant plastic strain component near the mouth of the pit, while the principal stress is at a minimum there. Reduced constraint to plastic flow is considered to explain the location of extended deformation.

In terms of the impact on cracking, whether fatigue or stress corrosion cracking, it is evident that the mechanical contribution is always greatest near the pit mouth. For fatigue loading at low mean stress the tendency for cracking will be towards the mouth as both stress and strain are localised in that location. For stress corrosion cracking or for fatigue loading at high mean stress the plastic strain will be induced near the pit mouth. As noted previously, even with a constant applied stress there can be a dynamic component of the plastic strain because of the effect of a growing pit on the local stress and strain field.

Whether cracking originates near the pit mouth will depend on local chemistry and electrode potential in the pit as well as the mechanics. Furthermore, there may be local topographical features that could cause some stress/strain localisation. These factors need to be taken into account but the central message is that the common assumption that cracks start from the pit base has no intrinsic validity.

6 CONCLUSIONS

At high applied stress the localisation of plastic strain towards the pit mouth is accentuated (compared with hemispherical pits) for pits with the shape of a truncated sphere with depth greater than the radius, representative of those formed in 12Cr turbine blade steels.

At low applied stress, the stress and the strain (now purely elastic) are both a maximum near the pit mouth.

The results suggest that from a purely mechanical perspective there will be a tendency for cracking to initiate near the pit mouth but other factors, such as local chemistry, electrode potential and topography, may influence the extent to which this prevails in environment assisted cracking.

7 REFERENCES

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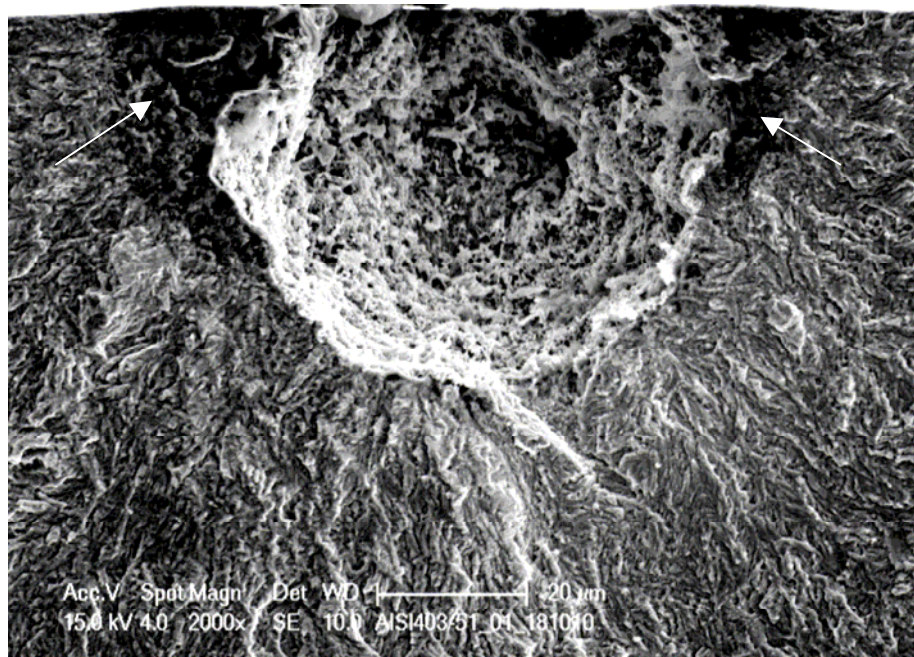


Figure 1 Fracture surface of a steam turbine blade fatigued in air at high frequency at 90 °C from a pre-existing corrosion pit. The dark zones on either side of the pit (arrowed) relate to a non-propagating short crack. The crack was then extended at a higher stress amplitude.

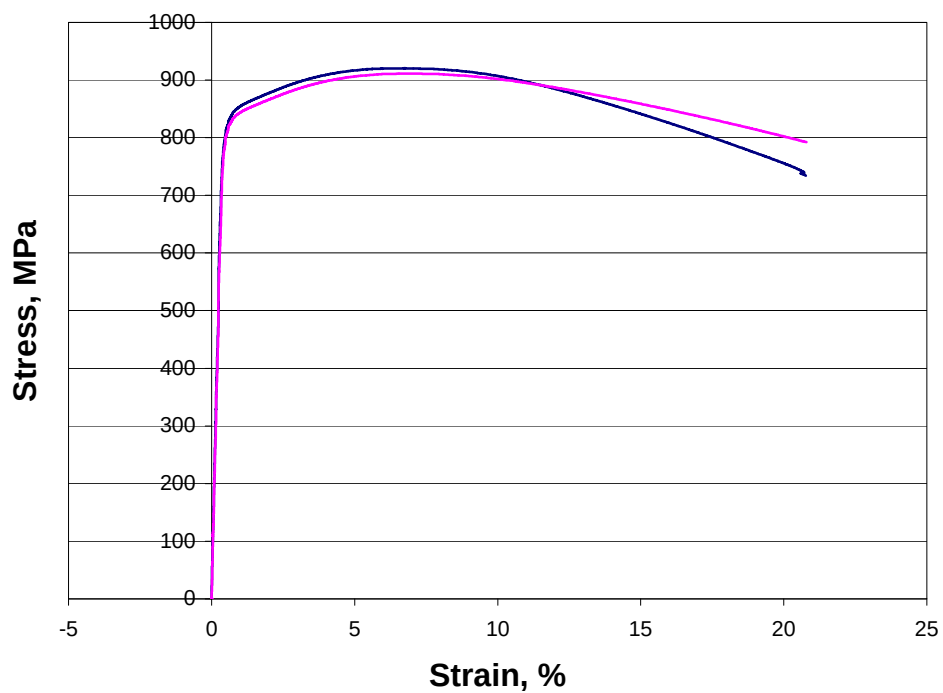


Figure 2 Stress-strain behaviour for a FV566 steel in air at 90 °C.

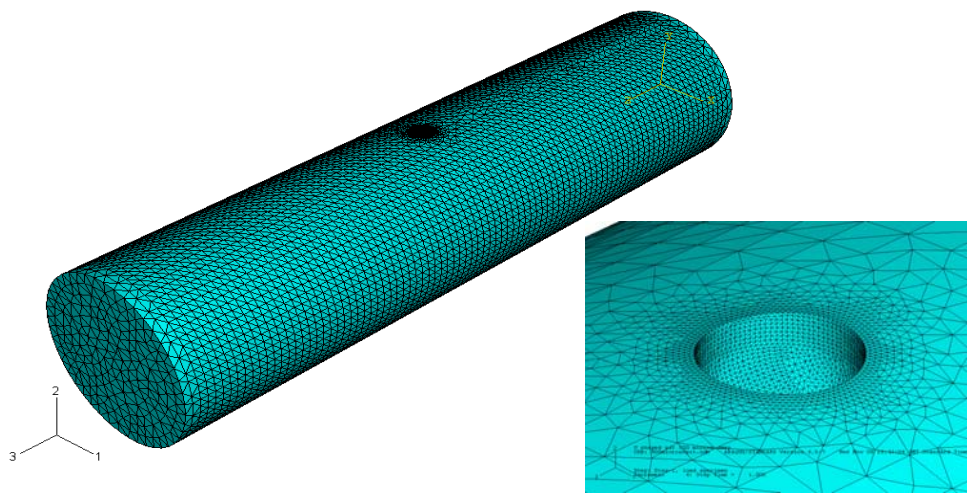
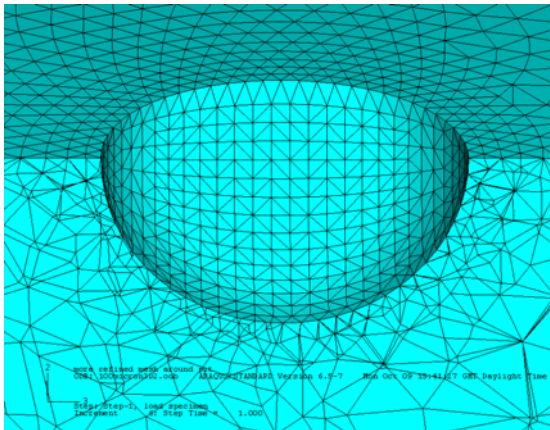
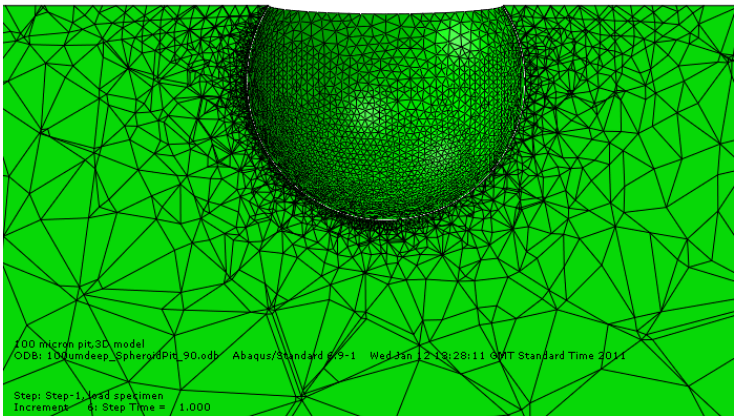


Figure 3 Specimen geometry illustrating mesh structure around 100 μm hemispherical pit. Specimen is axially loaded.



100 μm hemi-spherical pit



100 μm deep truncated-spherical pit

Figure 4 Pit geometries showing meshing.

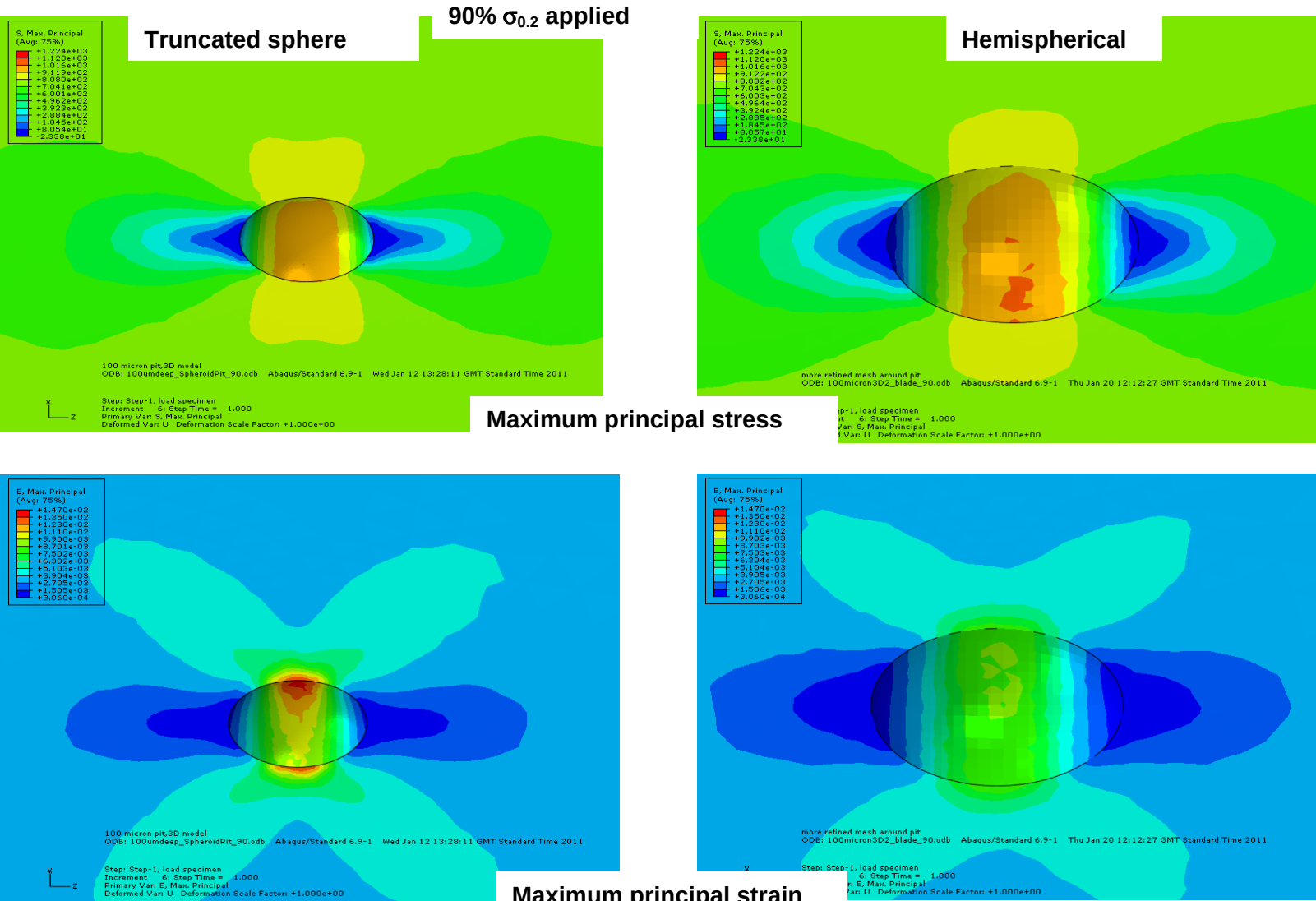


Figure 5 3-D view at applied stress of 90% of 0.2% proof stress.

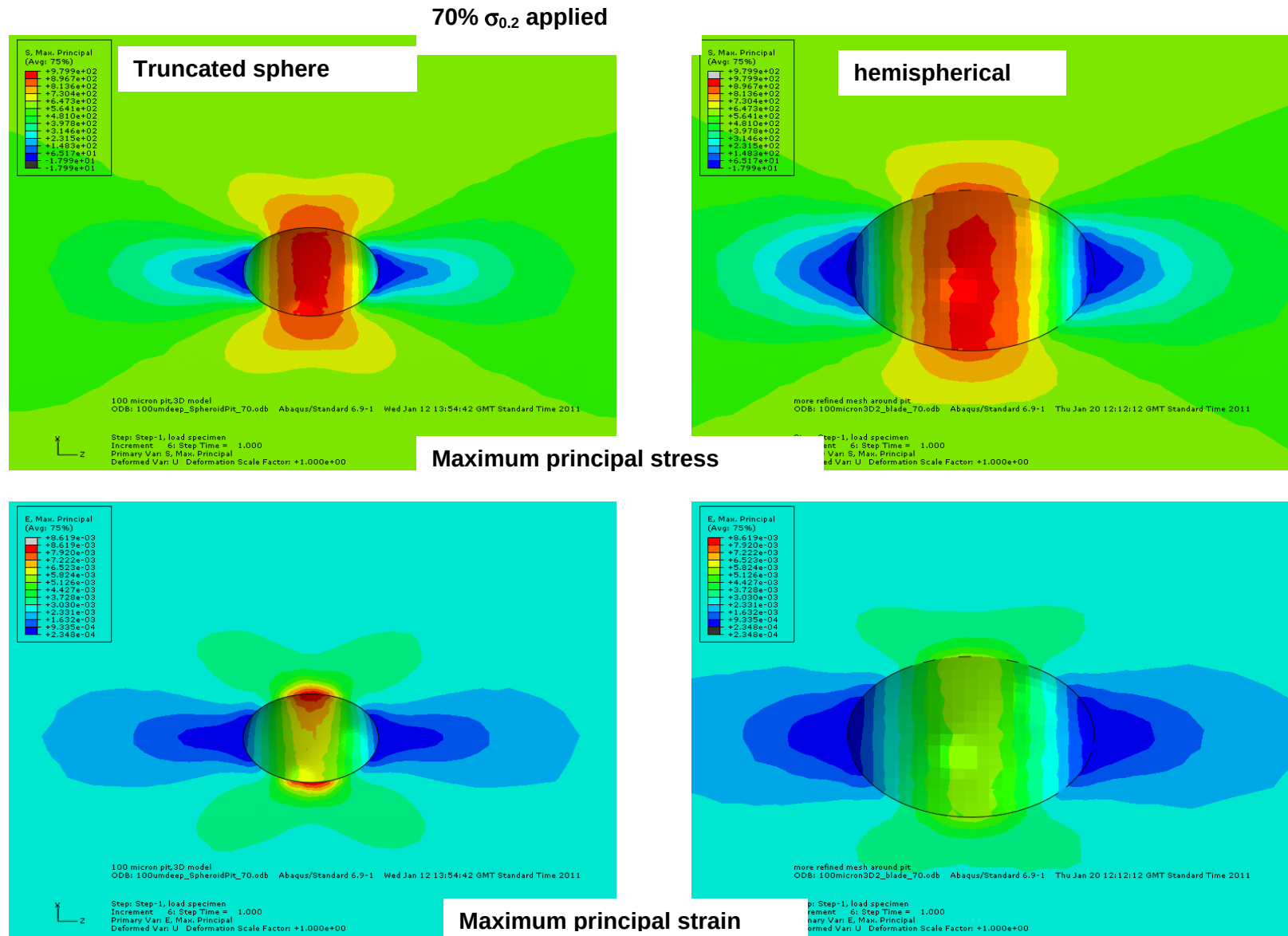


Figure 6 3-D view at applied stress of 70% of 0.2% proof stress.

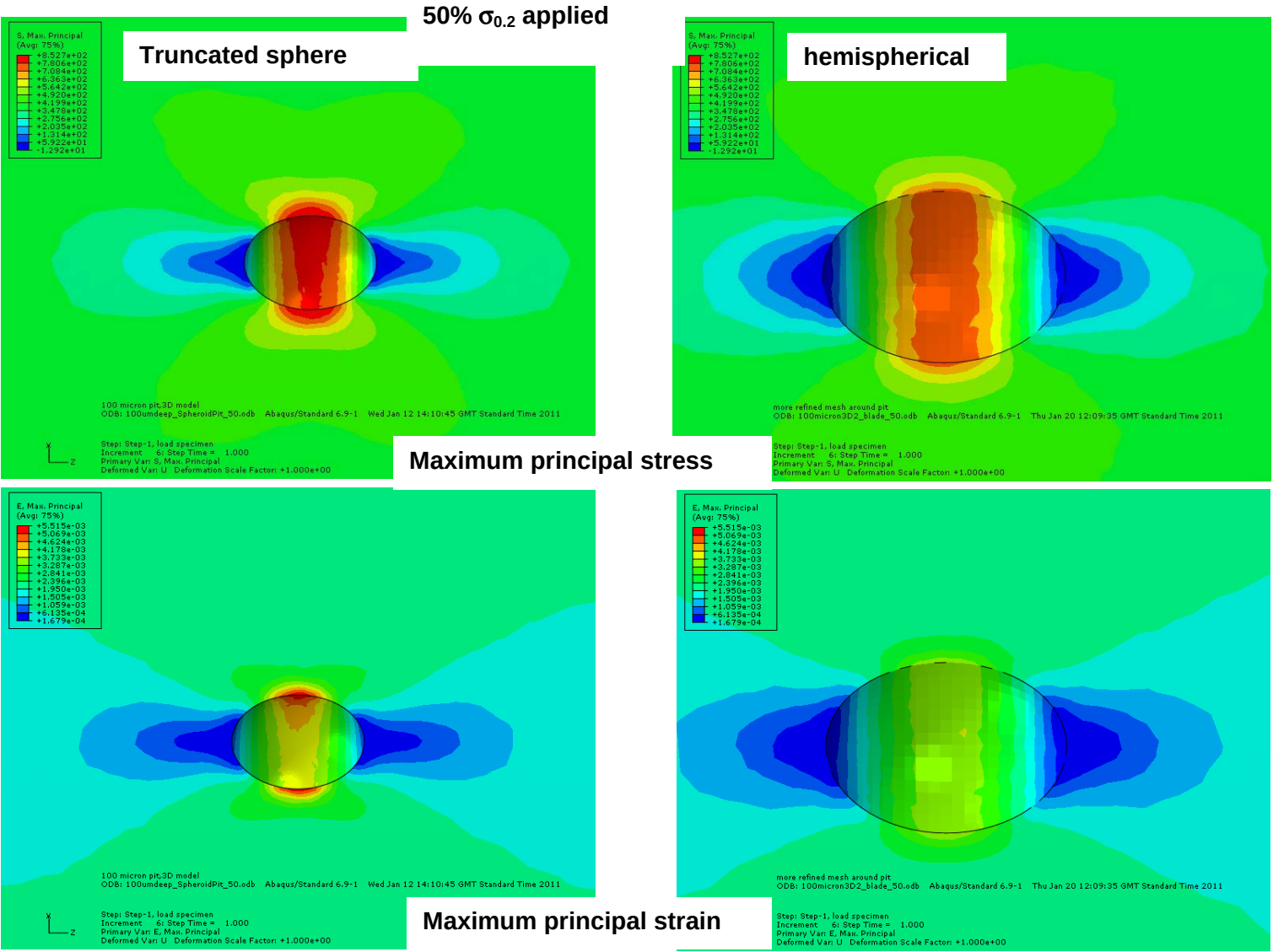


Figure 7 3-D view at applied stress of 50% of 0.2% proof stress.

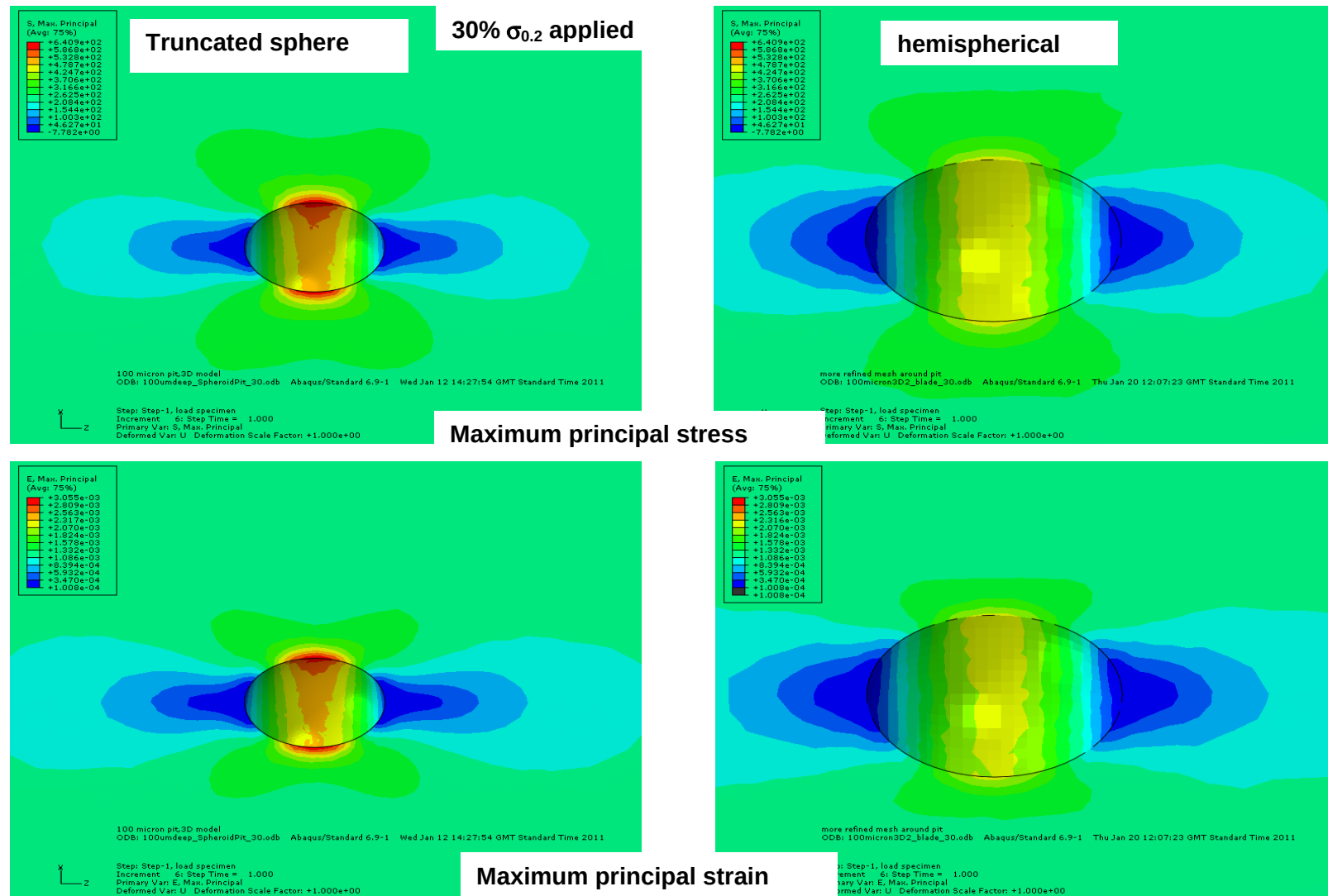


Figure 8 3-D view at applied stress of 30% of 0.2% proof stress.

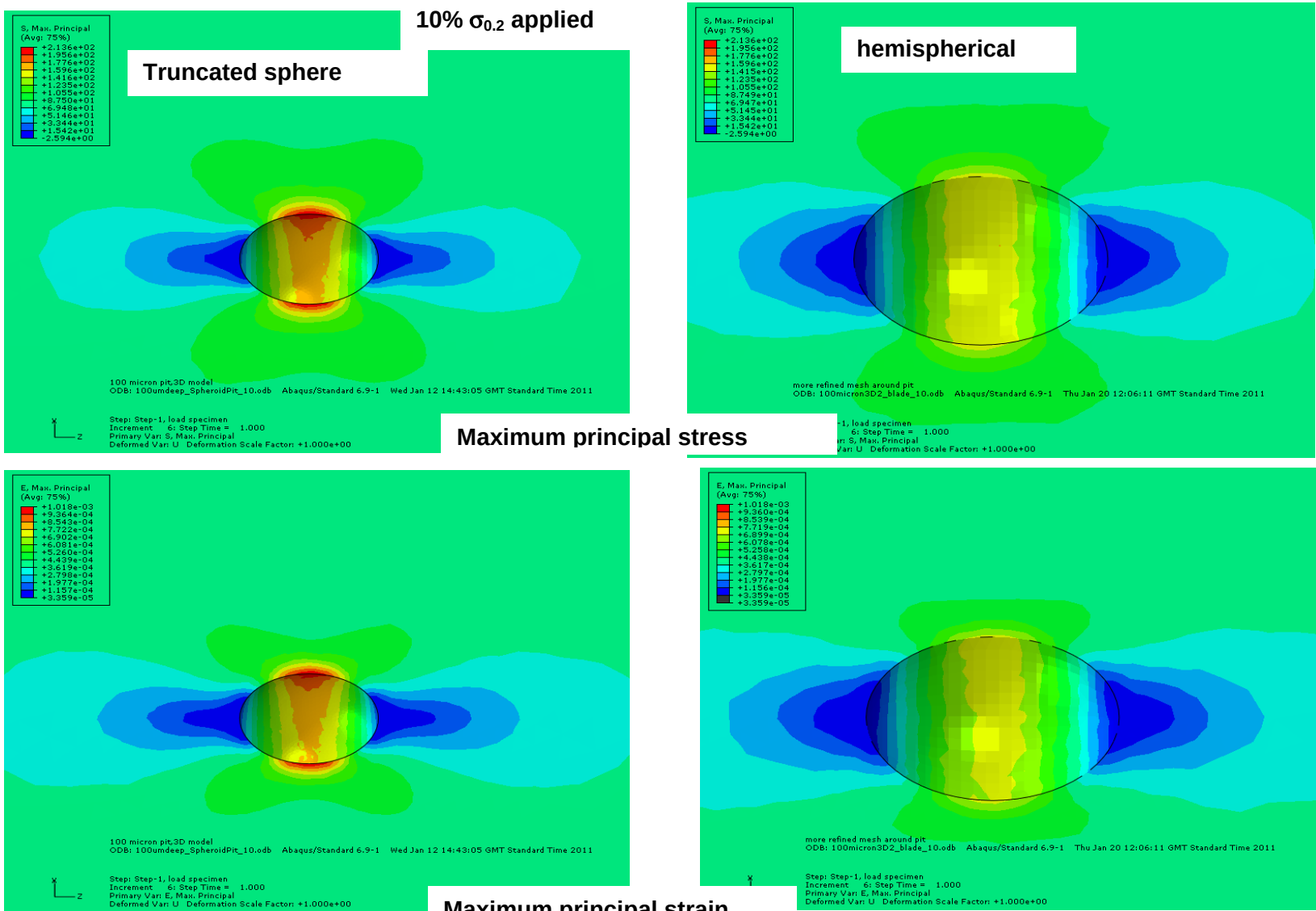


Figure 9 3-D view at applied stress of 10% of 0.2% proof stress.