CRACK MODELLING IN POWER PLANT COMPONENTS

International Conference on Pressure Vessels And Piping
Chennai, India
Feb 7-9 2006

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Abstract

Much of the process plant designed in the early 1970s, in response to increased demand for power, is now 'ageing' and necessitates an on-going 'fitness for service' assessment. This is necessary to satisfy licensing authorities requirements for continuous operations. Fitness for service assessment involves many issues including evaluation of structural flaws, material degradation, damage due to creep, fatigue and plasticity and the overall effect on the residual life of components. Codes of practice such as API 579, BS 7910 and R6 give detailed assessment procedures and may involve very detailed and time consuming finite element analyses. The authors have developed an FEA tool, Zencrack, to accurately evaluate single or multiple cracks in any structure (e.g. pressure vessels, piping, etc.). Further, 3D non-planar crack growth under general fatigue or time dependent loading is possible. The software can help to increase efficiency in performing sensitivity studies, thus allowing more accurate assessment of the residual life of the plant than would otherwise be possible in a given timeframe.

Keywords: Zencrack; J-Integral; Failure Assessment Diagram; Life Assessment

1. INTRODUCTION

Regulatory authorities, world-wide, require that 'fitness-for-service' assessment of the existing process plant and equipment such as pressure vessels, piping, storage tanks and other high pressure equipment is carried out on a regular basis to satisfy operational reliability and safety requirements. This type of assessment also helps in life management of the equipment involving scheduling of planned inspections, maintenance, repairs, life extension, shutdowns and eventual retirement. The assessment involves thorough structural inspection using various visual and non-destructive techniques to identify location, shape and size of flaws, misalignments and other structural defects, etc. Also as the equipment ages the materials, due to the repeated and sustained loading and environmental conditions, degrade. Fitness-for-service assessment requires an evaluation of the effects of these flaws and material degradation on the structural safety of the equipment using fracture mechanics methodologies.

2. FRACTURE MECHANICS METHODOLOGIES

Fracture mechanics methodologies have evolved since the early 1950s and involve metallurgical, structural and computational mechanics aspects, which are well described in various text books, national standards and other literature. New developments and further understanding in each of these areas have moved us forward to estimating more accurately 'safe design life' of the structures. Depending on the industry, generally, methodologies described in BS 7910, CEGB R(6), API 579 and other national codes are accepted by most licensing authorities. For the conservative assessment of flaws most of the codes advocate simplified procedures. In general, however, use of these methodologies in assessing 'fitness-for-service' of ageing components is considerably more involved and time consuming.

In this paper emphasis is given to the computational aspects of modelling and evaluation of shape, size, non-planar growth, interaction and stability of flaws in aging structures subject to sustained and time varying loads using finite element techniques.

3. COMPUTATIONAL ASPECTS

The fracture methodologies generally require the stress intensities or the energy release rates of the crack to be obtained. In addition the plastic collapse load is often of interest. For simple geometries, loading conditions and materials, empirical equations exist. Further difficulties may arise if there are multiple defects close together. Although codes of practice give guidance on simplifying these scenarios, the finite element method is the tool of choice for detailed assessment work.

Use of the finite element method for fracture mechanics assessments usually requires the use of complex 3D models since 2D models are generally not appropriate for practical geometries. In general, calculation of the j-integral is required for this type of work although the Ct-integral may be required for creep assessments. Accurate calculation of the j-integral or Ct-integral requires the use of a focused mesh, which is difficult to produce for general 3D cracks.

4. BRIEF INTRODUCTION TO ZENCRACK

Zencrack [1] is a software tool that allows the use of various finite element codes such as Abaqus [2] for detailed 3D fracture mechanics simulation. The program has been developed to allow easy generation of 3D finite element meshes with complex crack shapes. This, however, is only part of the process. The subsequent finite element analysis and post-processing of the results are carried out by Zencrack to reduce the otherwise onerous manual effort in this type of work. The program makes it easy to carry out a parametric study to improve the confidence in the results. Fully automatic crack growth prediction is also possible and has been used extensively in the aerospace industry. These capabilities make the program highly suited to any analysis where large numbers of crack sizes or load conditions must be considered or where crack growth is of critical importance e.g. breakthrough problems, leak before break, ductile tearing, generation of failure assessment diagrams.

Zencrack uses a crack-block methodology. The basic approach is explained in Fig. 1 for the use of standard crack-blocks. A normal uncracked mesh is produced using any pre-processor. The user then selects the desired crack-blocks. Zencrack produces a new cracked mesh with the crack-blocks mapped into place with the correct boundary conditions and the requested crack size and shape.

Zencrack can be used to undertake fatigue crack growth to determine the number of cycles to failure or to obtain energy release rates for larger cracks (e.g. for a parametric study or a J-R analysis). A brief example of crack growth is shown in Fig. 2. The crack growth run took 75 finite element runs. A new mesh with the updated crack front coordinates is automatically made for each finite element run. In addition to having several options for input of crack growth data, a load system methodology is utilised to allow different combinations of loading. This includes variable amplitude loading and the combination of static loading with cyclic loading.

A detailed explanation of Zencrack is beyond the scope of this paper. The general program background is available in a number of papers e.g. [3-5]. Here we will concentrate on several aspects that are of relevance to power plant components.

5. EXAMPLES

The following examples have been selected to demonstrate the capabilities of Zencrack for the assessment of power plant components:

- Sweepolet – an example of a parametric study
- Water box – an example of complicated geometry
- Reheater drum – an example of creep
- Multiple flaws
  - Two cracks in a plate
  - Nozzle
- Crack growth
  - cyclic bending of a pipe
  - interaction of two eyebrow cracks

An interesting example involving complex loading, not described in this paper, is the study of the effects of crack propagation on a pipeline subjected to seismic loading [6].

5.1 Sweepolet – An Example Of A Parametric Study

The codes have empirical formulas to obtain stress intensity factors and collapsed loading of pipes. However the formulas are generally difficult to apply to complicated geometries such as a sweepolet.

The stress intensity factors along the crack front and the collapse load were obtained for the sweepolet for a variety of crack combinations and load conditions:

- A series of inner and outer wall cracks, ranging from 10% to 60% of the wall thickness were placed at the weld locations with the header and branch.
- Eight load cases were applied.

Meshes for all crack sizes were automatically produced by Zencrack from three basic uncracked meshes (quarter symmetry, half symmetry and full depending upon the load case). The example given (see Fig. 3) is for a quarter model 30% inner wall branch crack. Multi point constraints were used to tie the shell elements to the 20 noded hex elements.

5.2 Water Box – An Example Of Complicated Geometry

The waterbox consists of a chamber with inlet and outlet pipes, a tubeplate section across the top and cover plates at the bottom as shown in Fig. 4. The tubeplate region contains many bore holes, most of which were modelled using a transversely orthotropic material model. In the example shown, three separate defects were included at the bore of a drain hole located close to the edge of the tubeplate region. In other analyses alternative defects were introduced near the same drain hole, and at various depths along the upper internal radius of the main waterbox chamber. Due to the complexity of the tubeplate and the potential size of the model, the analysis was conducted in three stages using submodelling:

- analysis of a quarter symmetry global model
- first submodel : details of the drain hole and nearby tubeplate holes are included
- second submodel : cracks are introduced
- in the global model and first submodel the compliance of the crack was simulated by release of degrees of freedom on the symmetry plane to give a crude approximation of the crack position.

Pressure and thermal transient analyses were carried out to provide stress intensity factors along the crack fronts.

5.3 Reheater Drum – An Example Of Creep

This analysis is of an embedded defect located in a re-heater drum wall. The crack modelling is made more difficult by the nearby pipe. The full model and cut-away plots of the crack are shown in Fig. 5. The model was analysed under pressure load and a thermal transient. In addition, a creep analysis was conducted in order to determine the time to steady state and the C* values along the crack front. A plot is shown of the Ct-integral values for one crack front node as a function of time. This clearly shows the path dependence in the Ct-integral evaluated from 3 contours until steady state (and C*) is reached after approximately 10000 hours.

5.4 Multiple Flaws

One area where the codes are very conservative is using traditional methods for creating FADs with multiple cracks. Multiple cracks often have to be combined together and treated as one large crack. However if an API 579 level 3 assessment using FEA is undertaken then the unmodified flaws can be inserted into the mesh.

The example in Fig. 6 is for two elliptical cracks in a plate subjected to an axial load. The crack dimensions are a_1=a_2=0.1389, c_1=c_2=0.1667, s_1=0.1389, and s_2=0.1667. Using the recommended rules (see Fig. 7) results in a combined flaw dimension of a=0.3473 and c=0.4168.

Creating a failure assessment diagram using FEA for the two single cracks results in an increase in failure load of 20% over the combined single crack. (This is for an API 579 level 3 assessment using FEA. The material used is representative of SA 516 grade 70 steel.) The procedure for creating a failure assessment diagram for an API 579 level 3 assessments is explained in [7].

A second example is shown in Fig. 8 for a nozzle. The model utilises cyclic symmetry. The same uncracked model was used to evaluate 10 different crack combinations/sizes using Zencrack. Meshes for two different crack combinations are shown. This example is explained in more detail in [8].

5.5 Crack Growth

The first crack growth example is of a pipe with manufacturing defects. The operators wanted to know the possible operational life of the defective pipes. The defects have been modelled as a circumferential crack. The pipe is subjected to a cyclic positive bending moment.
A Zencrack crack growth analysis was undertaken (see Fig. 9) to determine the number of cycles to rupture. A Paris crack growth curve was used to determine the rate of crack growth. Some of the crack growth profiles (35 finite element runs were required) and the crack growth curve can be seen in Fig. 9. As expected only the top half of the crack grew due to the positive bending moment. References [3-5] explain the details behind a Zencrack crack growth run.

The second example of a crack growth run is the interaction of two eyebrow cracks [9]. The Zencrack crack growth profiles can be seen in Fig. 10.

6. CONCLUSION

Pressure vessels with a number of nozzles, pipes protruding externally and a maze of tubing internally, generally develop awkwardly shaped cracks at locations near weld connections. The codes allow the use of finite element analysis to analyse the components and determine accurate stress intensity factors and limit loads. In order to obtain confidence in the results one needs to carry out a sensitivity study requiring a number of FE analyses using various sustained and time varying loads.

In many cases engineers are reluctant to use finite element analysis because of the difficulties of producing cracked meshes. However we have introduced a tool called Zencrack that significantly reduces the time required to produce cracked meshes and process the analysis results. In addition Zencrack can undertake accurate crack growth predicting the direction of crack growth, the crack profiles and the number of cycles to failure.

7. REFERENCES

1. Zentech International Limited, Mytchett, Camberley, Surrey, U.K. http://www.zentech.co.uk/zencrack.htm
2. Abaqus, Inc., Pawtucket, Rhode Island, U.S.A. http://www.abaqus.com
3. Timbrell et al, "State Of The Art In Crack Propagation", Journée Scientifique 2004: Les méthodes de dimensionnement en fatigue, Centre de Compétences Matériaux & Conception (CCM&C), Fribourg, Switzerland, Oct 27 2004. http://www.zentech.co.uk/zencrack_publication_zentechpaper.htm
4. Chandwani et al, "An FE Simulation Tool For Fracture Mechanics", International Seminar on "Fatigue, Reliability & Performance Considerations In Design", Indian Institute of Science, Bangalore, India, Jul 14-15 2005.
5. Timbrell et al, "Recent Developments In 3D Fatigue Crack Growth Prediction Using The Finite Element Method", FENET Technology Workshops - Durability and Life Extension, Noordwijk, The Netherlands, Oct 9-10 2003.
6. T. Iijima, "Simplified modelling and detailed crack propagation analysis for cracked pipes", Proceedings of PVP2005, Denver, Colorado USA, July 17-21 2005. http://www.zentech.co.uk/zencrack_publication_zentechpaper.htm
7. P. S. Lam, T.S Sindelar, "Comparison of fracture methodologies for flaw stability analysis of storage tanks", WSRC-MS-2004-00209, Westinghouse Savannah River Company, Westinghouse Savannah River Technology Center, Aiken, South Carolina USA.

8. Wiehahn et al, “Failure Assessment Diagrams from 3D Finite Element Analysis”, FENET Technology Workshops - Durability and Life Extension, Palma, Majorca, Mar 25-26 2004. http://www.zentech.co.uk/zencrack_publication_zentechpaper.htm
9. Bezensek, Hancock, “The re-characterisation of complex defects, Part I: Fatigue and ductile tearing”, Eng. Frac. Mech. 71, 2004 (981-1000)

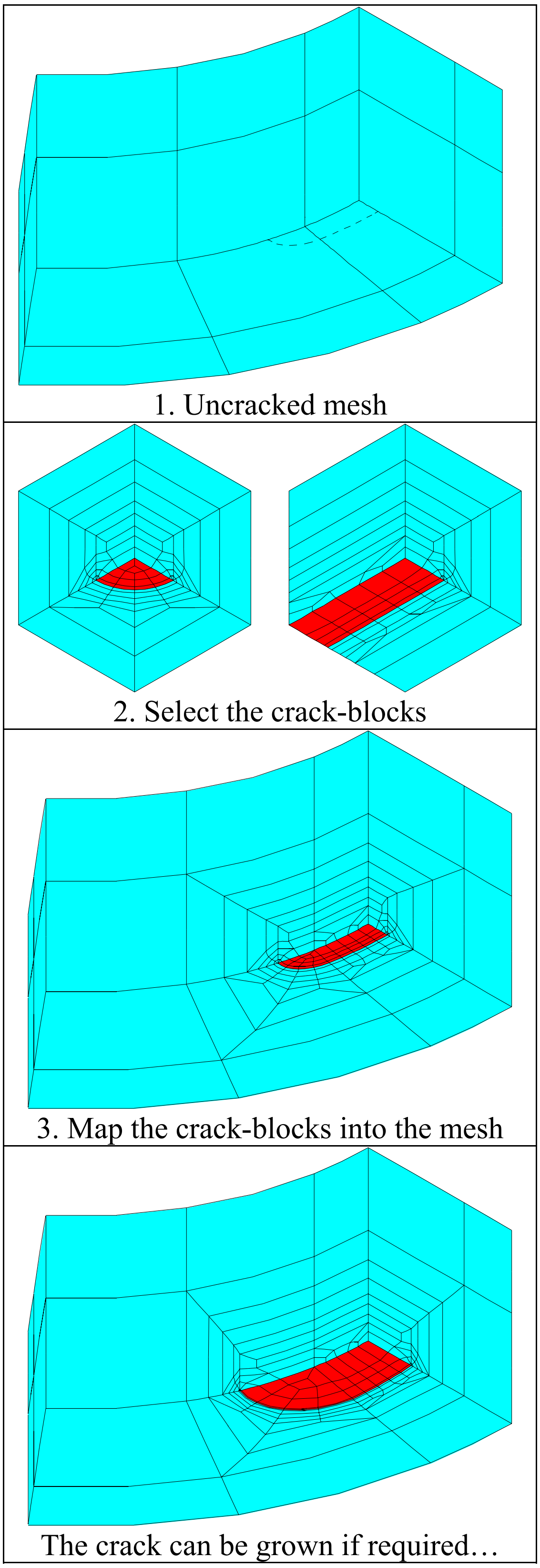


Fig. 1 – Inserting a crack into a mesh using Zencrack

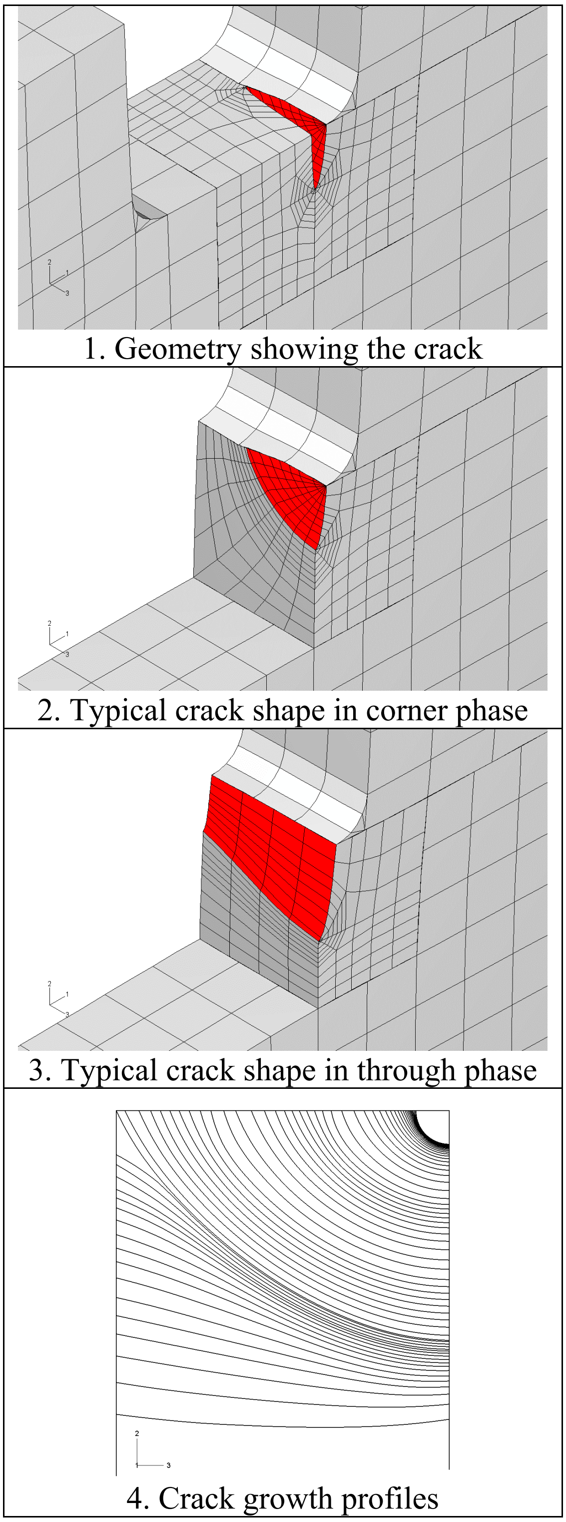


Fig. 2 – Demonstration of crack growth using Zencrack

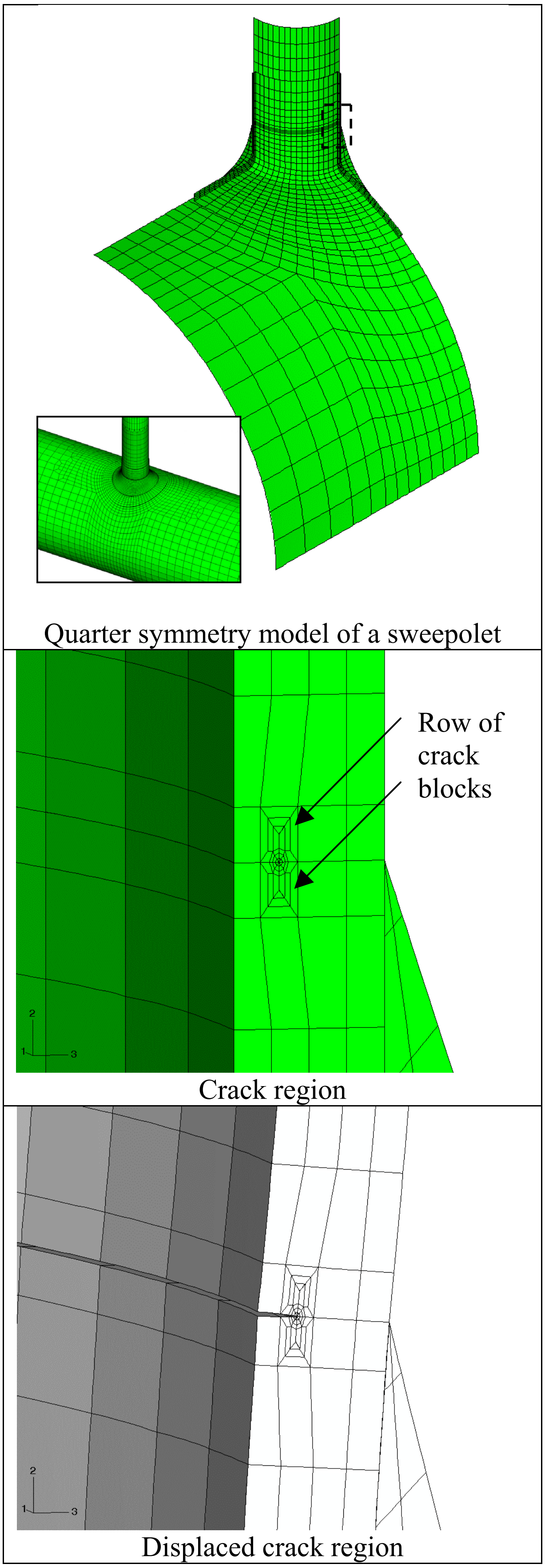


Fig. 3 - Sweepolet – an example of a parametric study

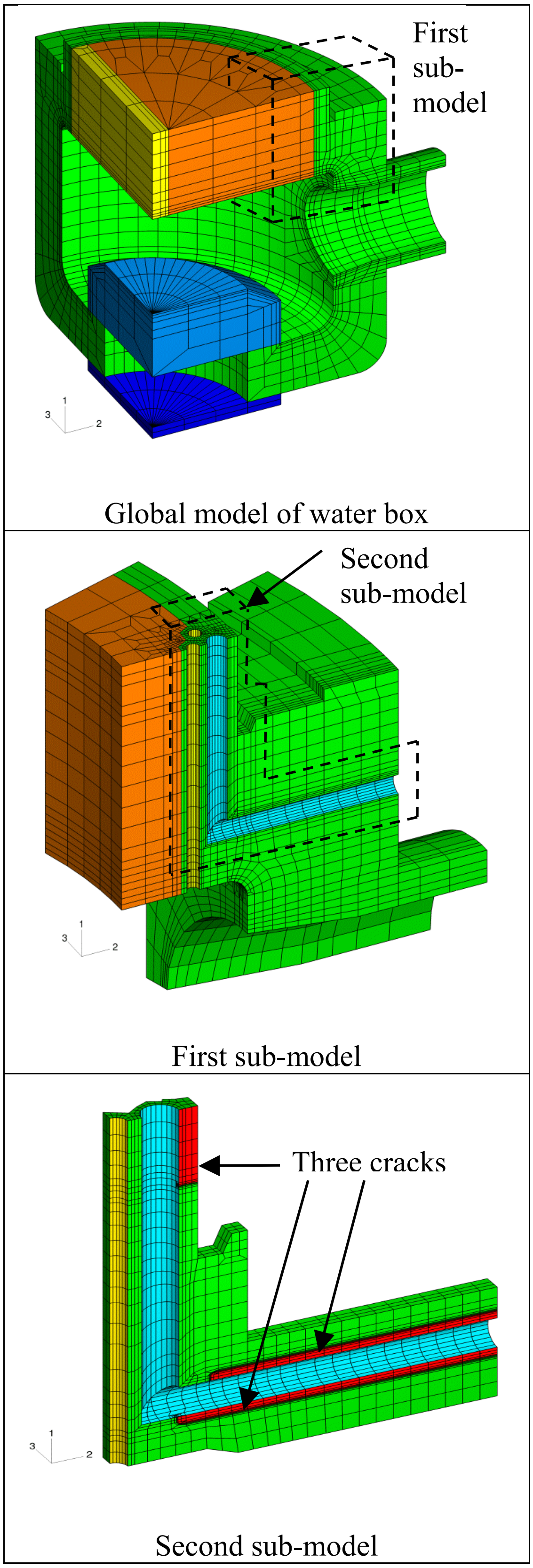
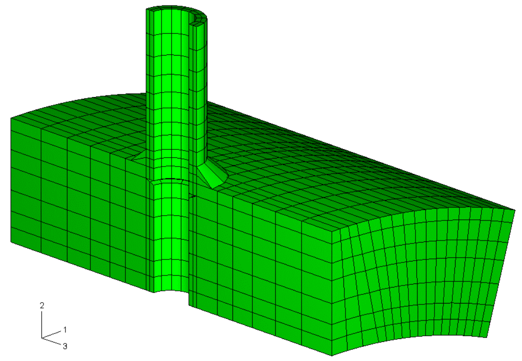
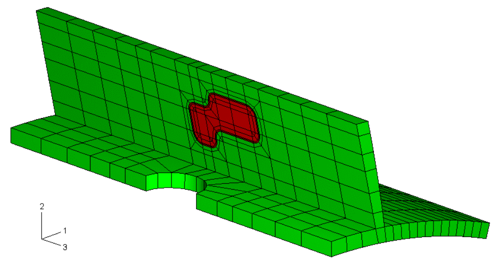


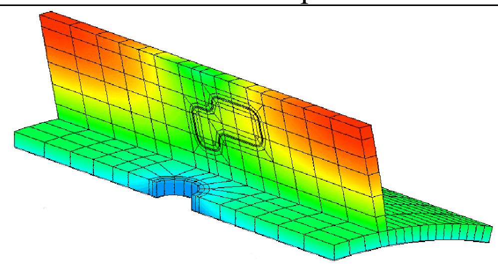
Fig. 4 – Water box – an example of complicated geometry



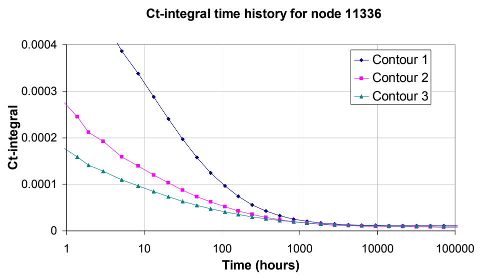
Entire model of re-heater drum



Location and the shape of the crack

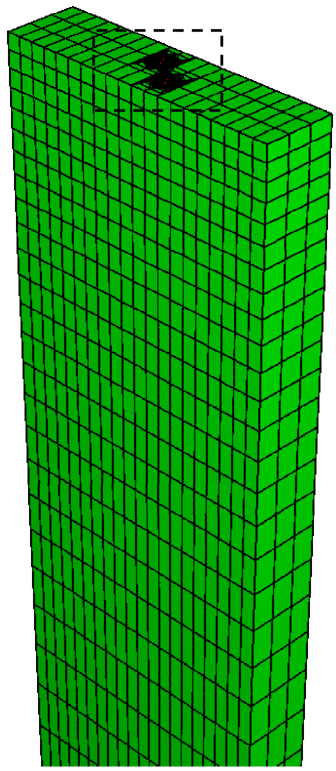


Temperature distribution



Convergence of Ct-Integrals to C* at steady state after 10000 hours

Fig. 5 – Reheater drum – an example of creep



Cracked mesh with two elliptical cracks.

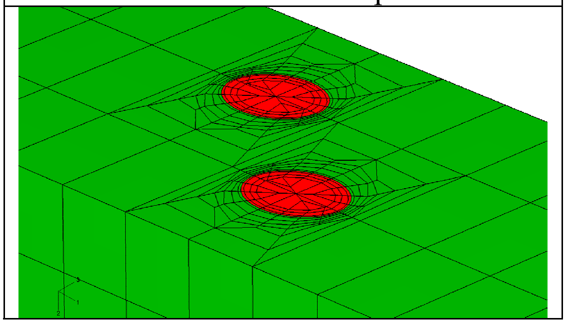
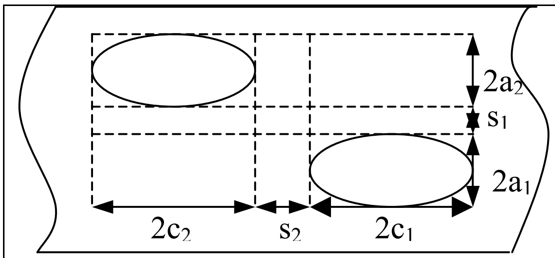


Fig. 6 – Multiple flaws – Two cracks in a plate



Criterion for combining flaws	Combined flaw size
$a_1 + a_2 \geq s_1$	$2a = 2a_1 + 2a_2 + s_1$
$c_1 + c_2 \geq s_2$	$2c = 2c_1 + 2c_2 + s_2$

Fig. 7 - Suggested rules for combining flaws in API 579

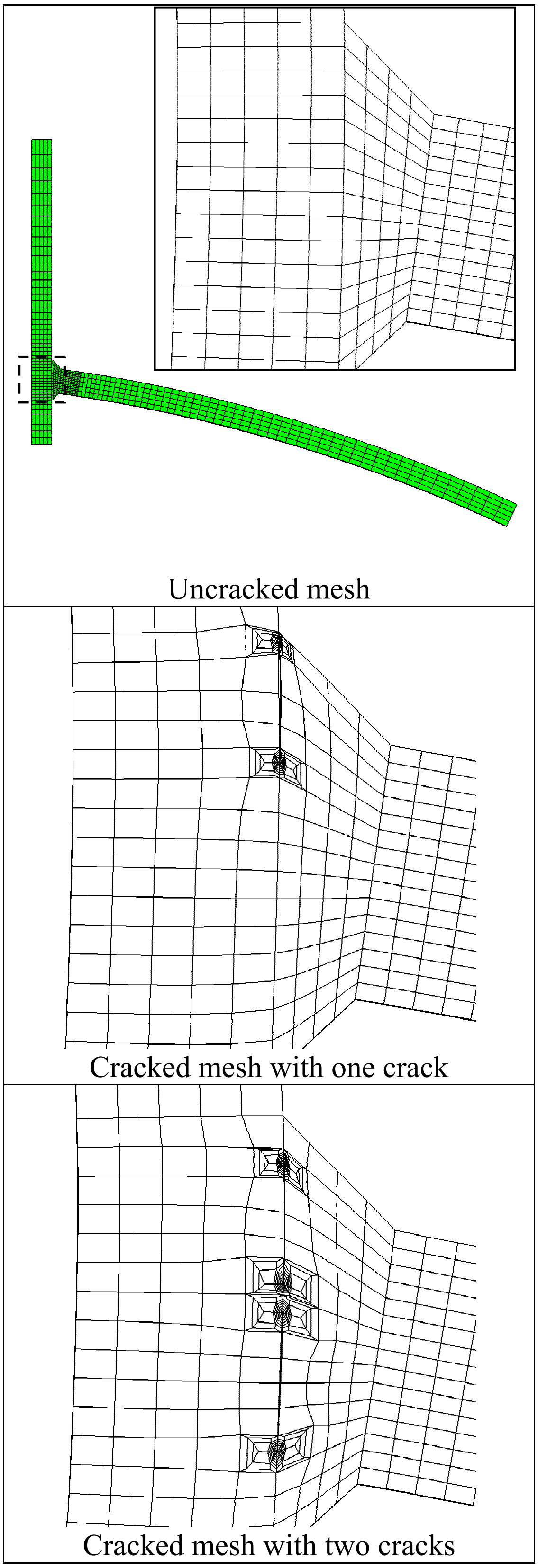


Fig. 8 - Multiple flaws – a nozzle

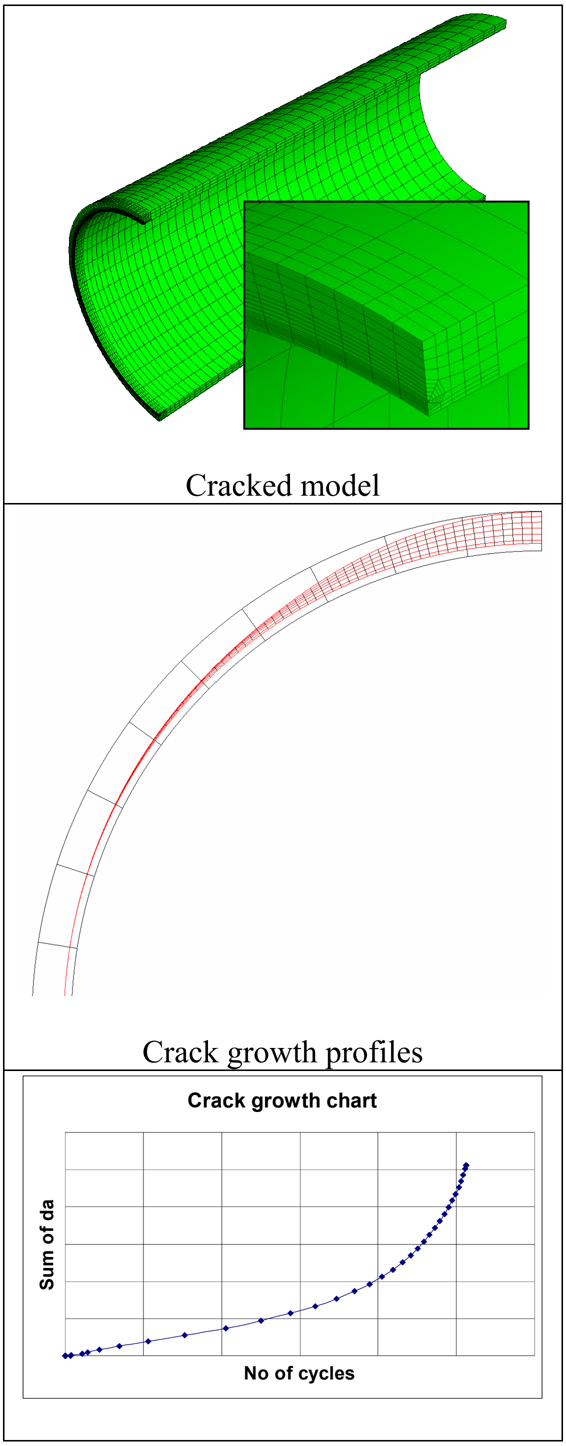
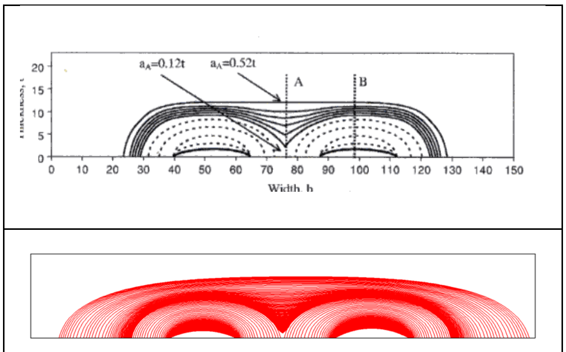


Fig. 9 - Crack growth – cyclic bending of a pipe



Simulated crack profiles

Fig. 10 - Crack growth – interaction of two eyebrow cracks