

SIMULATION OF CONTAINMENT-TESTS OF FAST-SPINNING ROTORS BY EXPLICIT FEM

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ABSTRACT:

The objective of Containment Tests is to demonstrate that the housing of a turbocharger is of sound design and capable to satisfactorily contain fractured rotating parts inside the casing. As of yet these tests were carried out on a test bed during the type approval procedure of the turbochargers. On one hand this is very expensive and time consuming and, on the other hand, the comprehension of high-speed deformation processes is restricted as well as the possibilities for measurements and improvements are limited. Due to these reasons containment tests were simulated using the explicit finite element technique, which is implemented in the code LS-DYNA. The results of the simulations which were carried out were used to improve the performance of the turbocharger in containment safety. Regions of high loading of the structure could be identified and improved. For validation purposes a test was carried out on the test bed. The results of this test have shown excellent correspondence to calculation results of the simulation with respect to global and local deformations and the mechanical behaviour of the charger components.

KEYWORDS:

Containment Test, LS-DYNA, turbocharger, highspeed deformation, explicit FEM

INTRODUCTION

The containment test discussed in this paper is carried out in order to provide a safe and reliable design of turbochargers that are used for diesel engines on vessels. For preparation of the test sample three notches are cut into the compressor wheel spaced 120 degrees apart. The compressor wheel will then burst during operation at the weakened sections due to high local stresses caused by the centrifugal forces. The condition to pass the containment test is that no part of the rotor leaves the housing of the turbocharger. In order to reduce costs and also to provide a deeper insight into the mechanics of the problem simulation techniques shall be used. By these techniques the fracture process can be monitored, which usually is not available at regular burst tests. Whereas a test provides the final result (safe containment demonstrated or not) and possibly some measures (mostly accelerations and strains) the results of a simulation may be viewed in every section of the machine so that stresses, strains, deformations, interacting of parts and much more information can be obtained. Slow motion animations are possible for any of these results. Moreover design changes can be studied very quickly once a simulation model is generated.

SUBJECT OF INVESTIGATION

The subject of investigation is an *axial-flow turbocharger* with an output of 5,100 kW used for Diesel engines on vessels. It consists of a radial compressor and an axial turbine, a gas-admission casing and a gas outlet diffuser at the turbine side, a compressor volute and a diffuser at the compressor side. The shaft on which the turbine wheel and the compressor wheel are mounted is situated in a bearing casing. The maximum permissible speed is about 26,000 1/min. The total mass of the charger is between 1,050 and 1,350 kg at a length of 1,300 to 1,900 mm, a height of 1,400 mm and a width of 950 mm.

CONTAINMENT TEST

MODEL CHARACTERISTICS

The model consists of brick elements as well as shell and beam elements. Shells are mainly used in regions with less importance for the local mechanical effects of the rotor burst. Beams and rigid elements are used for the connection of different parts. The entire model consists of about 630,000 elements including structural and contact elements. The smallest elements in this model do not fall below a length of 2 mm. Figure 1 shows a section through the simulation model of the turbocharger.

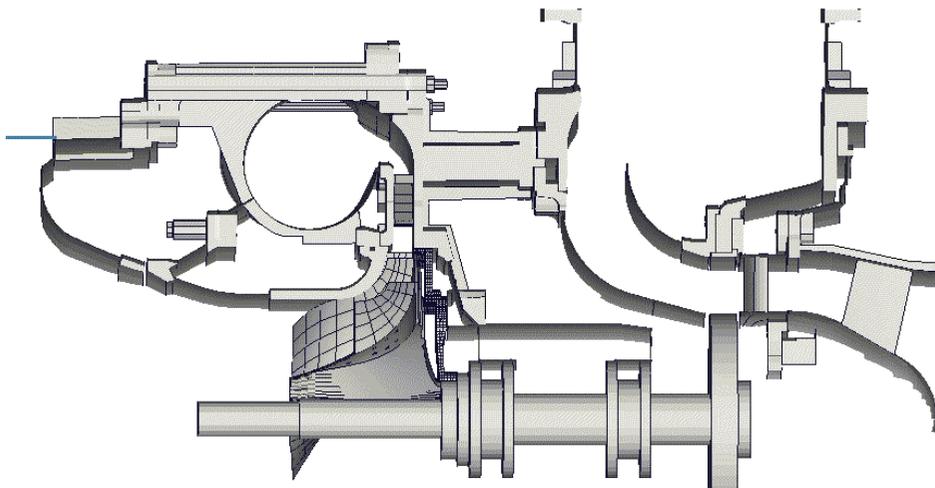


Figure 1: Section through the Simulation Model of the Turbocharger

In Figures 2 – 4 the most important parts for the lapse of the crash are displayed. They show again the distribution of volume and shell elements in the direct surrounding of the slotted impeller wheel.



Figure 2: Simulation Model – Entire Turbocharger and Compressor Wheel

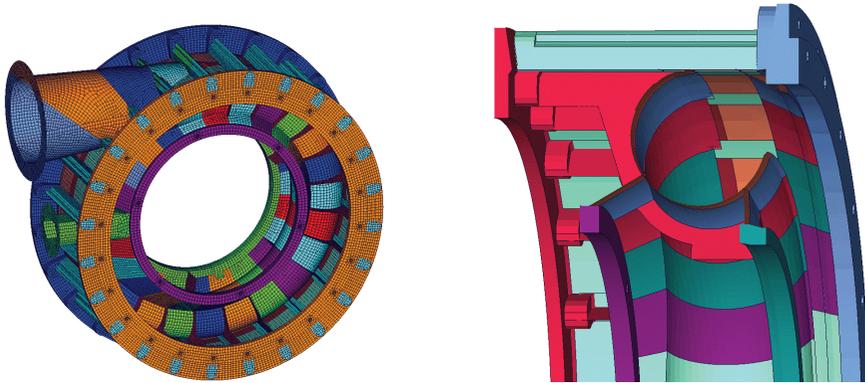


Figure 3: Simulation Model – Compressor Housing

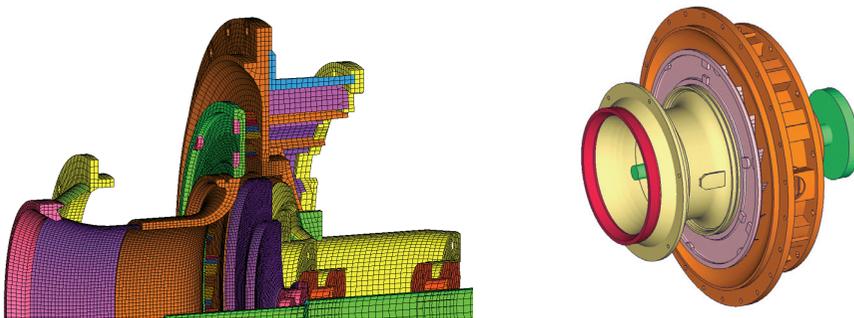


Figure 4: Simulation Model – Insert Piece and Bearing Housing

The main body of the compressor wheel is built in three parts, all of which consist mostly of hexaedron and a small number of pentahedron elements. The strong deformations especially at the outer rim of the fragments afford very thin shell elements to avoid contact instabilities. Those shell elements surround the volume elements in the border areas of the impeller parts and are assigned a *MAT_NULL material model. This way the influence on mass and stiffness of the three parts is very small.

The screws used in this model each consist of several beams connected in a row. To simulate the contact between the screws and the flanges they connect, MAT_NULL contact shells are built as a face around the screws.

APPLICATION OF BOUNDARY CONDITIONS

The contact that affords the main part of the calculation time in this model is a *CONTACT_AUTOMATIC_SINGLE_SURFACE. Most structural parts of the turbocharger that may get into contact are defined here. A definition of this contact for all volume elements would consume too much performance and time. For this reason single layers of thin shell elements are applied to the inner surfaces of the volume parts in regions where the impeller fragments are supposed to impact the housing. Here an extra contact of the type *AUTOMATIC_NODES_TO_SURFACE is defined between the outermost shells of the fragments and the thin contact shells on the volume parts.

The impeller blades, as well as the blades of the diffuser are subdued to very high strains. In the simulated burst case they are most likely to get sheared in the blade root. To include this effect into the simulation material failure was defined for those blades. When reaching a certain plastic strain they are taken out of the model. This was reached by defining the PSFAIL criteria in the cards of the MAT_PIECEWISE_LINEAR_PLASTICITY.

When the calculation starts, the impeller fragments are supposed to radially move from the shaft into the housing. This effect was reached by applying an INITIAL_VELOCITY_GENERATION to the volume elements, the blades and the contact shells of the impeller parts. It was defined for a rotation of the fragments around the shaft with the maximum permissible speed.

The material type mainly used in this model is a MAT_PIECEWISE_LINEAR_PLASTICITY. Due to the highly dynamic deformation processes during the simulation a strain rate dependent material model is necessary to obtain reliable information. Moreover the parts are assigned a material law for their specific temperatures. While high strain rates increase the strength of metal and make it brittle, high temperatures normally lead to a decreasing strength but higher ductility. Figure 5 shows an example of a material used in this simulation.

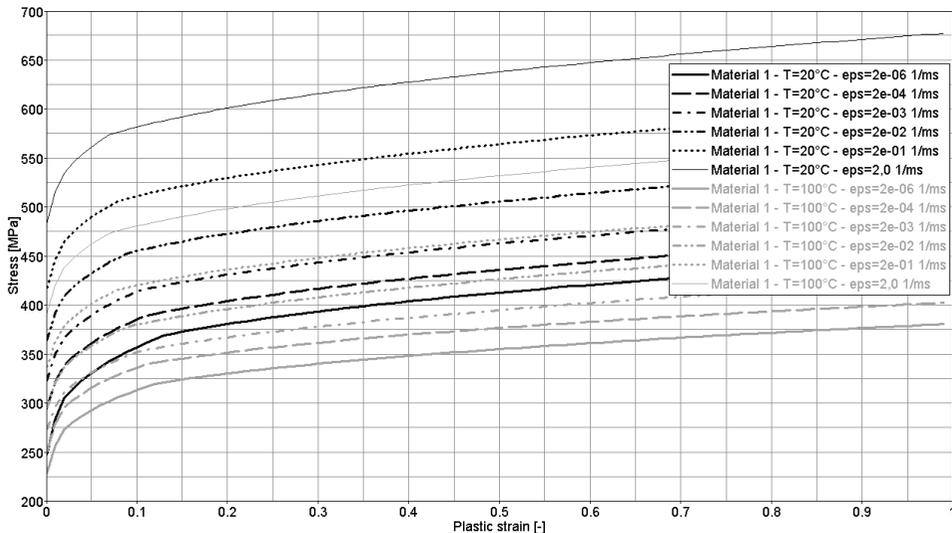


Figure 5: Example of a Material Law

CONTAINMENT TEST

With the above shown finite element model the containment test was simulated using the explicit finite element software *LS-DYNA*. The whole containment test, which actually lasts about 2.0 to 2.5 milliseconds, is simulated in about 75,000 time steps of 0.035 microseconds. Using a *LINUX-Cluster* with four CPUs the simulation CPU-time is about 20 hours.

SIMULATION RESULTS

In the beginning of the simulation the three parts of the compressor wheel are located on the shaft. The forces resulting from the applied initial velocity lead to a *radial movement* of the impeller parts which results in the contact of those parts and the housing within an actual time of approximately 0.1 milliseconds. The fragments of the impeller intrude into the housing at about 1.2 milliseconds. After this time the impeller parts are stopped. Due to *dynamic mass effects* the structure of the housing reaches its maximum loading with a delay of about 0.5 milliseconds. After this time the elastic forces of the housing result in an acceleration of the parts of the impeller back towards the shaft.

Figure 6 shows the *distribution of internal energy* in different parts of the turbocharger over time. After about 0.5 milliseconds the impeller intrudes severely into the housing. About 50 % of the total kinetic energy of the impeller is transferred into internal energy of the structure within the first 2 milliseconds. Another 50 % of the total initial energy remains in kinetic energy in the moving parts. 80 percent of the internal energy is mainly inherent in five parts which are the main structure of the compressor housing of the turbocharger.

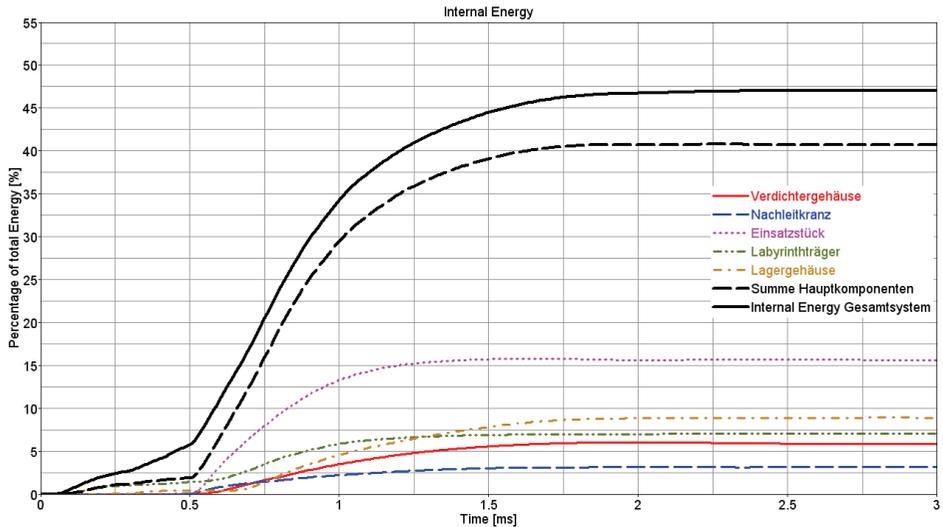


Figure 6: Internal energy content for different parts

Figure 7 shows the intrusion of the impeller parts at different phases during the simulation. For a better understanding of the effects and the mechanisms during the containment test these results may *also be viewed in animations*. It is also possible to animate results which are calculated during the simulation such as *stresses or plastic strains*.

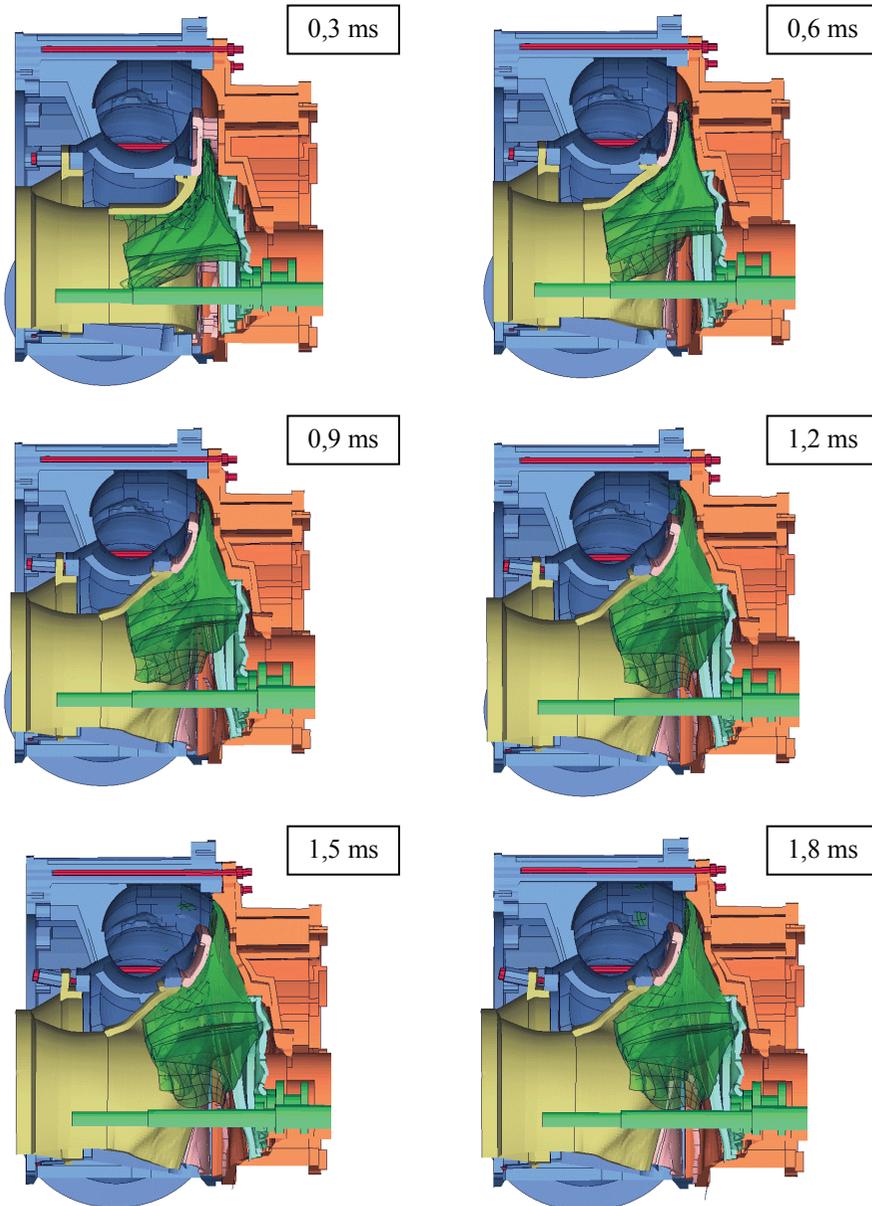


Figure 7: Kinematics in the Compressor Section during the Simulated Containment Test

COMPARISON TO REAL TESTS

For validation purposes a real containment test was carried out at the test rig. After the test the turbocharger was disassembled photographs could be taken from the individual parts. These photographs can be compared to the corresponding parts of the finite element model after the simulation. Figures 8 through 11 show a *good conformity* between test and simulation results. Figure 8 shows the three parts of the impeller after the containment test.

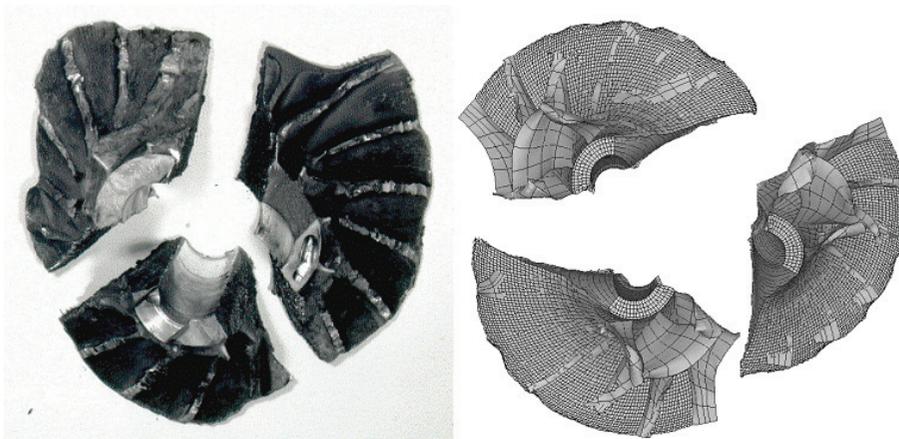


Figure 8: Impeller

For most materials no failure was considered in the simulation. However a plastic strain of 35% to 40% can be considered to be a realistic failure strain. Figure 9 shows the results for the insert piece. Cracks can be observed in regions of plastic strains greater than 40%.

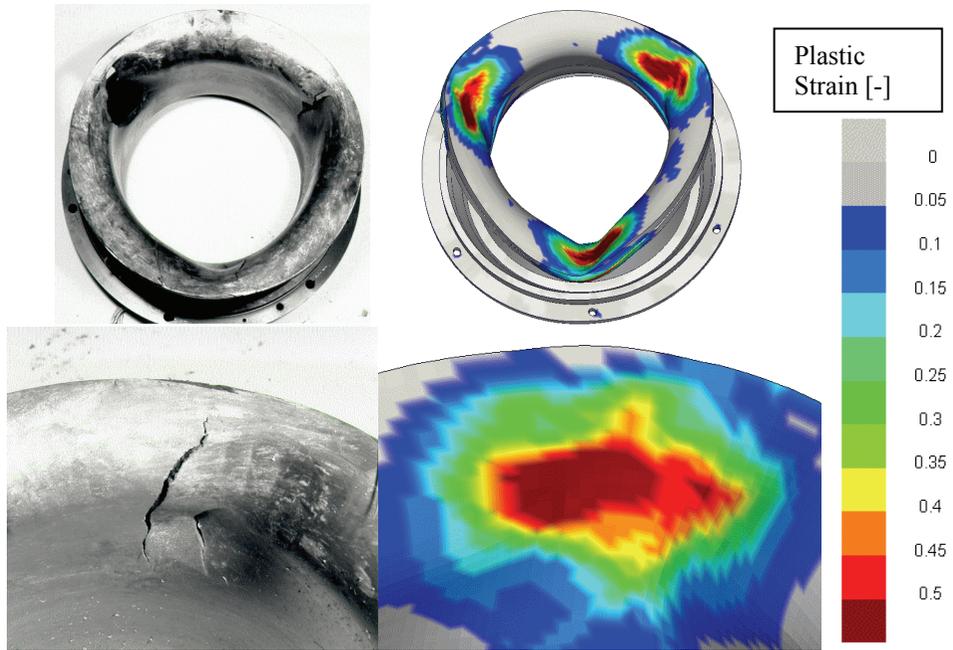


Figure 9: Insert Piece



Figure 10: Labyrinth Ring

The calculated deformations of the labyrinth ring shown in figure 10 are in good accordance to the test result. Even the crack initiations at the blades of the diffusor (figure 11) are represented in the simulation results. For this material and element configuration failure strains were considered.

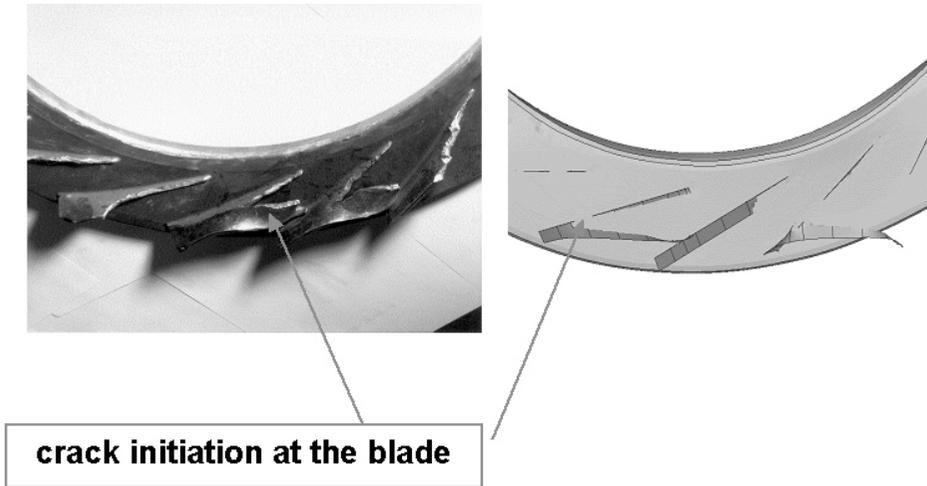


Figure 11: Diffusor Blades

SUMMARY AND CONCLUSIONS

Simulation results were observed to be in excellent conformity to the test results. The predicted damages of the components are very similar to the damages of the tested components. For regions in which no material failure was considered in the material law, high plastic strains occurred where the tested specimen failed.

The numerical analysis is able to predict high stressed regions and even cracks in the components. Containment safety by the numerical analysis can be used instead of containment tests.

Moreover the simulation shows a high potential during the development process of turbochargers and other fast spinning rotating machinery. The insight in the mechanics and the kinematics of the machine is much deeper using simulation techniques. Design changes can be evaluated much faster and less expensive than by testing on the test rig.

The results show a good concurrence between test and simulation even where no material failure was modelled. Nevertheless modelling material failure by using an ultimate plastic strain criterion enhances the agreement between test and simulation. This should be investigated in future work.

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