Crashworthy design of a heavy 6-axle diesel locomotive

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Abstract: The Voith Maxima® 40 CC is the world's most powerful single-engine diesel-hydraulic locomotive. Its carbody was dimensioned in such a manner that it can withstand the static loads due to EN12663. Also the fatigue strength had to be ensured. In addition the locomotive has to fulfil the standard crash scenarios due to the new European standard prEN15227. The whole dimensioning of the carbody and also of the bogies was done with ABAQUS/Standard and ABAQUS/Explicit.
The main focus in this paper is on the simulation with ABAQUS/Explicit of the required crash scenarios with different obstacles. Especially the assembly of the full scale crash model will be discussed in greater detail. It consists of the carbody with all equipment, bogies with wheelsets and the coupling elements. Thereby extensive use was made from different connector elements available in ABAQUS. Also the external crash buffer elements with their energy absorbing characteristics were modelled by means of special connector behavior features. The contact between wheel and rail is also included. Before the actual crash the spring deflection of the primary and secondary suspension due to gravity is considered. Thereby the resulting oscillations have been minimised by means of the FORTRAN user subroutine VDLOAD.
Finally the frontal crash of two identical locomotives with a vertical offset will be shown where the benefits of the crashworthy design will be apparent.

Keywords: Carbody, connector elements, offset crash, crash system, locomotive,

1. Introduction

1.1 Who we are

Helbling Technik AG is the biggest engineering company in Switzerland. It belongs to the Helbling Group and has about 160 employees, most of them with an engineering background. The main focus of Helbling Technik AG is the development of innovative products in close collaboration with its clients. The clients are mainly major companies from industries as automotive, telecommunications, aerospace, medical technology, machinery manufacturing, transportation and railway vehicles. According to this the core competences of Helbling Technik AG are on the fields of product innovation, mechanical design, electronic design, mechatronics,

automation and robotics, software engineering, optics and sensors as well as calculation and simulation.
The business unit ‘transportation and simulation’ is primarily specialized in the development of heavily loaded structures made of steel or aluminium. Thereby, the know how encompasses the whole development process from the first concept studies to the final production drawings. A very close collaboration between design engineers and calculation engineers guarantees a short and costly-optimized development time. The application of these heavily loaded structures is mainly in the aerospace and railway industry. For example Helbling Technik AG developed the complete test devices for the fatigue test of the Airbus A380 as well as the dummy engine pylon and the dummy nose landing gear, also for the testing of the A380. On the field of railway vehicles, Helbling Technik AG has its focus on carbody structures for locomotives, trams and passenger cars.

For the challenging and mostly safety-critical calculations of the structures, Helbling Technik AG has used ABAQUS since 20 years and has therefore a lot of experience available in finite element calculations with ABAQUS/Standard and ABAQUS/Explicit. To meet the growing demand of steadily increasing model sizes and simulation scenarios, ABAQUS runs on a LINUX cluster with 14 CPUs at present.

1.2 The diesel locomotive Voith MAXIMA® 40 CC

The development of the carbody of the diesel locomotive MAXIMA® 40 CC was done on behalf of and in close collaboration with Voith Turbo Lokomotivtechnik in Kiel, Germany. Voith Turbo Lokomotivtechnik develops, produces and sells this worlds biggest, single-engine diesel-hydraulic locomotive, see Figure 1. The 6-axle locomotive MAXIMA® has a maximum weight of 135 t and an engine power of 3600 kW which comes from a 16-cylinder diesel engine. The overall length is 23.2 m. The locomotive was presented the first time at the Innotrans in Berlin in September 2006.

The task of Helbling Technik AG has been the design of the carbody of the locomotive due to boundary conditions specified by Voith Turbo Lokomotivtechnik. Such boundary conditions have been for example the fixation points of the aggregates as engine, gear box, cooling unit etc. but also the connection of the bogies to the carbody.

The carbody had to be a welded, self-supporting steel structure which should be dimensioned in such a manner that it can withstand different static and fatigue loadcases according to EN12663 as well as several crash scenarios according to prEN15227.

As the available development time for the carbody was only eight month, a reliable and capable tool for the finite element calculation was essential. Furthermore this FE code must be able to cover implicit simulations as well as explicit simulations for the crash scenarios.

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Figure 1. The locomotive MAXIMA® 40 CC

2. Crash scenarios according to the European standard prEN15227

In April 2005 the new European standard prEN15227 was published. It contains different requirements concerning the crashworthy design of railway vehicles. Particularly three crash scenarios are defined. Scenario 1 describes the crash of two identical railway vehicles with a relative collision speed of 36 km/h, see Figure 2, while scenario 2 defines a crash with a freight car of 80 tons also at a speed of 36 km/h.

The purpose of a crashworthy design of locomotives is to limit the decelerations in case of a crash as well as the intrusions and to prevent the fatal climbing of the colliding partners. The decrease of deceleration and intrusion improves the safety of the driver but reduces also the forces onto the fixations of the aggregates as engine, gear box, etc. Especially in case of low speed crashes predefined deformation zones in combination with energy absorbing devices can significantly help to reduce the repair costs as only the crushed parts have to be replaced. In Europe crashworthy locomotives have been under investigation since the end of the nineties of the last century (Carl, 2004).

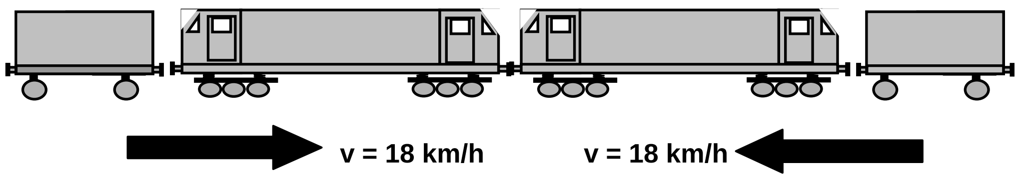

Figure 2. Crash scenario 1 according to prEN15227

Scenario 3 defines the crash with a heavy obstacle at a level crossing with a collision speed of 110 km/h, see Figure 3. The heavy obstacle can be interpreted as a lorry, which has a mass of 15 tons and a certain deformation characteristic. This characteristic has also to be verified by means of an impact simulation with a sphere.

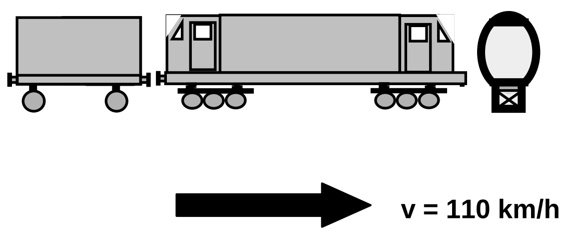

Figure 3. Crash scenario 3 according to prEN15227

In prEN15227 also a scenario 4 is defined. This contains requirements for the obstacle deflector but these are in fact static loadcases and are therefore not discussed in this paper.

3. Finite element model of the locomotive

The principal assembly of the carbody is shown in Figure 4. It consists of the base frame, the bogie sections, the driver's cabs, the side walls and the roof beams. As the carbody is self-supporting the framework of the side walls is essential to stiffen the structure against bending and to transmit the forces upwards into the roof beam. The diesel oil tank is integrated in structure and is also used for further stiffening of the base frame. The model of the carbody consists of S4R and S3R shell elements and is displayed without the fine meshes due to better visibility.

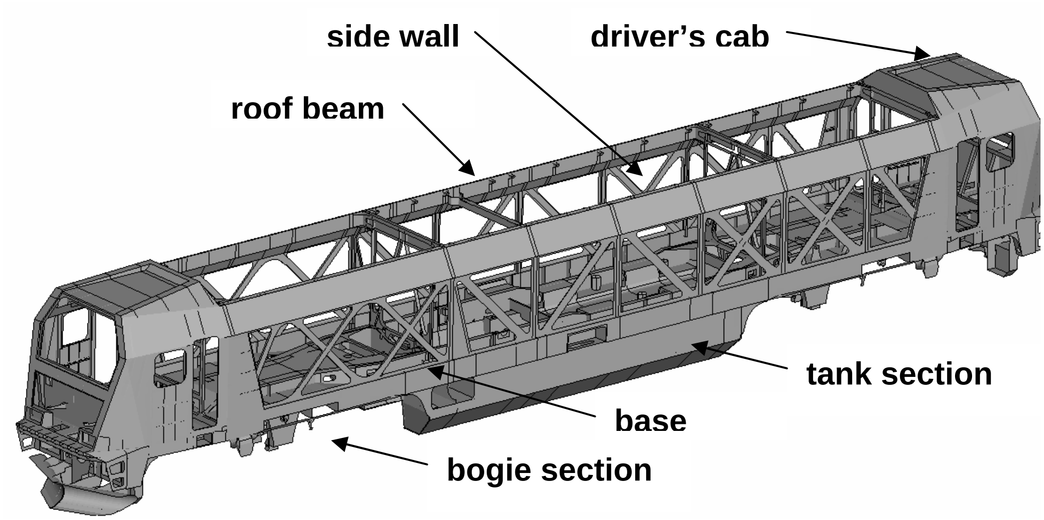

Figure 4. Finite element model of the carbody

Figure 5 shows the full scale model of the locomotive including all aggregates. These have been modeled as rigid bodies which are connected to the carbody via connector elements. The connector elements have the same stiffness and degree of freedoms as the real fixation parts. For obtaining a realistic load onto the fixation parts and their vicinity in case of a crash the modeling of the fixation stiffnesses should be as real as possible. Furthermore the decelerations of the aggregates in case of a crash are also determined to a certain degree by these fixation stiffnesses.

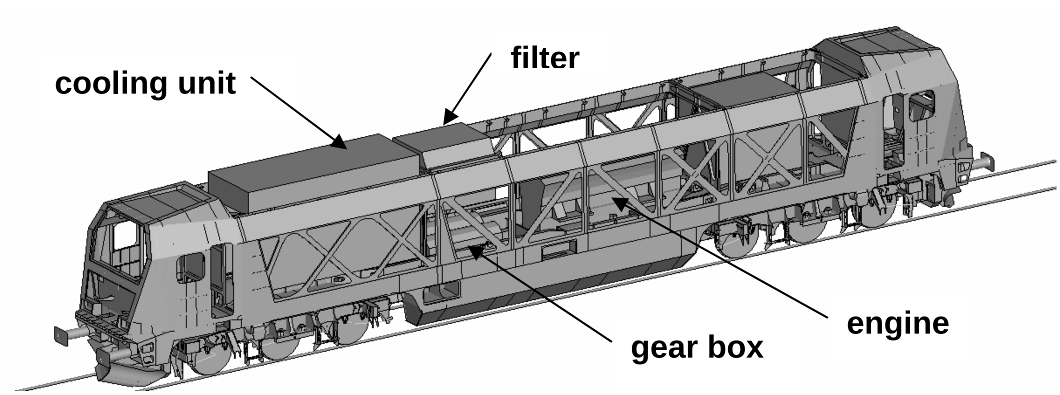

Figure 5. Finite element model of the full scale model

In Figure 6, the connection of the bogie to the carbody and the connection of the wheelsets to the bogie is showed in greater detail. Both the primary and secondary suspension was modeled by means of connector elements. The corresponding spring stiffness was assigned to these connectors, furthermore a connector stop was set to limit the vertical movement due to the movement stoppers in reality. In case of a crash it is important that the vertical kinematics are represented correctly as there is a considerable amount of vertical dynamics between the carbody and the bogie. Therefore also the spring deflection of the primary and secondary suspension before the crash due to gravity has to be taken into account. This was done via a connector reference length which is longer than the actual length of the connectors to produce a preload of the springs. This preload is equal for all the same springs but in reality there will be slight differences in x-direction due to the bending of the carbody. Therefore the initial position of the locomotive is in such a manner that it can drive the first 125 ms without colliding with the obstacle. This time is used for the calculation of the correct preloads in the connectors. To minimize the oscillations during this time a damping force in vertical direction is applied.

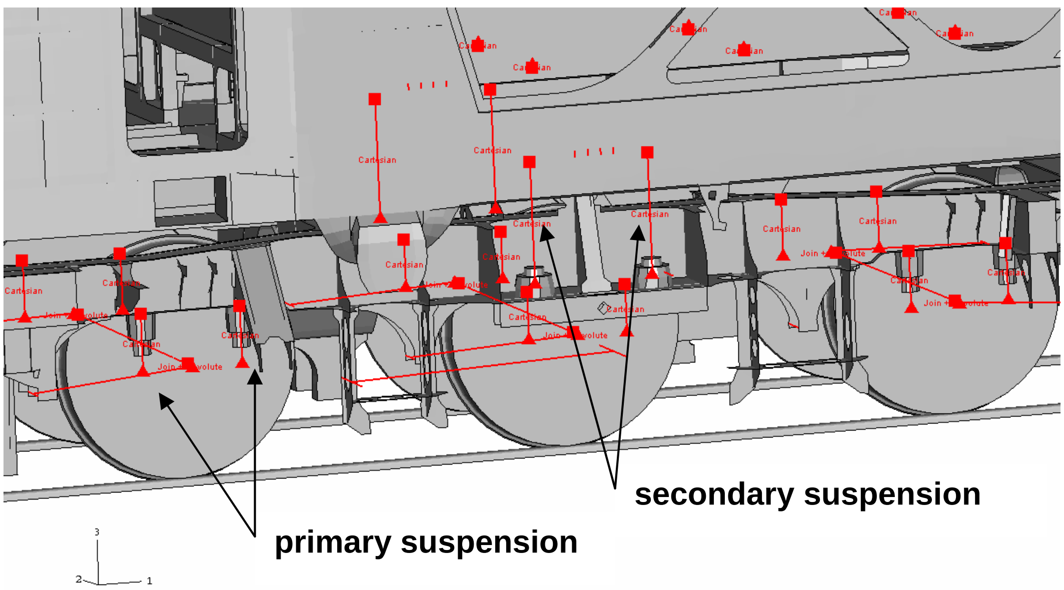

Figure 6. Connection of bogie

The following sample shows the modeling of the secondary suspension where lr is the reference length to generate the preload, cz and cy are the spring stiffnesses in vertical resp. horizontal direction and a and b are the limiting movement values. Also a small amount of damping d was applied. With one element it is possible to define the whole kinematic behavior in all three directions including movement restrictions. This is the main advantage of the connector elements.

```
*CONNECTOR SECTION, ELSET = sekundaerfeder, BEHAVIOR = sekundaerfederchar
CARTESIAN,
*CONNECTOR BEHAVIOR, NAME = sekundaerfederchar
*CONNECTOR CONSTITUTIVE REFERENCE
   ,     ,    lr
*CONNECTOR DAMPING, COMPONENT = 3
   d,    0.0,    0.0
*CONNECTOR ELASTICITY, COMPONENT = 1
   cy,    0.0,    0.0
*CONNECTOR ELASTICITY, COMPONENT = 2
   cy,    0.0,    0.0
*CONNECTOR ELASTICITY, COMPONENT = 3
   cz,    0.0,    0.0
*CONNECTOR STOP, COMPONENT = 3
  a,  b
```

The following Fortran user subroutine VDLOAD was used to apply vertical damping forces during the first 125 ms. Care has to be taken that the damping forces are not applied to the rotating wheels. This would decrease the initial kinetic energy over the first 125 ms and lead to a colliding energy which is smaller than the required one.

```
C User subroutine VDLOAD
      subroutine vdload (
     *     nblock, ndim, stepTime, totalTime, amplitude,
     *     curCoords, velocity, dircos, jltyp, sname,
     *     value )
C
      include 'vaba_param.inc'
      parameter (alpha = -0.001 )
C
      dimension curCoords(nblock,ndim), velocity(nblock,ndim),
     *     dircos(nblock,ndim,ndim), value(nblock)
*
      character*80 sname
*
      do k = 1, nblock
        value(k) = velocity(k, jltyp) * amplitude * alpha
      end do
*
      return
      end
```

ABAQUS offers also the capability to compute a static prestress implicitly and then to transform the stresses and displacements via the **`*IMPORT`** card into the explicit run. In fact, this would have been the way straight forward but we experienced a lot of difficulties with the **`*IMPORT`** card. Elements are partially not the same in Standard and Explicit, contact definitions are different, a considerable part of the model like rigid bodes, contact, couplings etc. has to be redefined in the explicit run. Here we would like an improvement of this capability in future versions.

4. Crash concept

As a consequence of prEN15227, a crash concept has to be incorporated which absorbs the kinetic energy in different stages depending upon the amount of the colliding energy. In the first stage the reversible elastomeric spring system of the buffers is active. In the second stage special energy absorbing crash elements are engaged, while in the third stage specially designed deformation zones in the underframe of the driver's cab begin to crush. Figure 7 shows an integrated deformation system that combines the stages one and two as described above. This particular system uses a combination of various irreversible plastic deformation modes (splitting and curling of a circular tube integral to the buffer casing, and the regular folding of a welded sheet metal box) to cover the second stage.

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Figure 7. Deformation system EST Duplex. Left: undeformed condition, right: fully deformed condition.

The overall force displacement behavior of such a deformation system is oscillating, and therefore, represents a considerable challenge for finite element analysis. The supplier provided a representative simplified characteristic which includes two force peaks Fa and Fb that are associated with the triggering of the different deformation modes (see Figure 8).

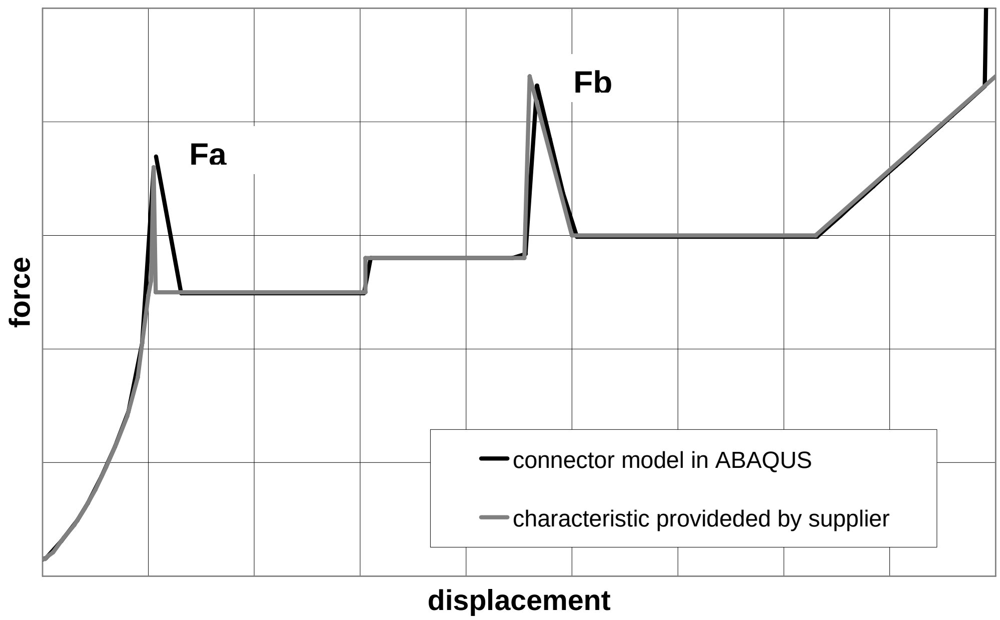

Figure 8. Force – displacement characteristic of the EST Duplex deformation system

The modeling of such a deformation element in ABAQUS is not trivial. It was done by means of connector elements with a special damaging behavior. Each buffer has been modeled by means of two connector elements.

The first one defines the elastomeric reversible spring system which corresponds to first stage of the crash concept described above. The nonlinear elasticity has been defined by implementing a list of forces (F1 to Fn) at the corresponding constitutive relative displacement (d1 to dn). The following keywords have been used:

```
*CONNECTOR SECTION, ELSET = Puffer_lok_lin, BEHAVIOR = Lok_lin_p
SLOT,ALIGN
*CONNECTOR BEHAVIOR, NAME = Lok_lin_p
*CONNECTOR ELASTICITY, COMPONENT = 1, NONLINEAR
F1, d1
Fn, dn
*CONNECTOR STOP, COMPONENT = 1
   a,   b
```

The second connector is neccessary to model the plastic deformation of the buffer corresponding to the second stage of the crash concept. This second connector defines the first triggering force Fa as well as the whole force-displacement characteristic as shown in Figure 8. The triggering force Fa has been implemented by using the keywords ***CONNECTOR ELASTICITY** and ***CONNECTOR DAMAGE INITIATION**. The description of the force-displacement characteristic is defined as a combination of the keywords ***CONNECTOR HARDENING** and ***CONNECTOR DAMAGE EVOLUTION**. With the parameters p, v, k the irreversible part of the force characteristic can be adjusted.

```
*CONNECTOR SECTION, ELSET = Puffer_feder_lok_p, BEHAVIOR = Lok_puffer_p
SLOT,ALIGN
*CONNECTOR BEHAVIOR, NAME = Lok_puffer_p
*CONNECTOR ELASTICITY, COMPONENT = 1
c,
*CONNECTOR PLASTICITY, COMPONENT = 1
*CONNECTOR HARDENING, TYPE = ISOTROPIC, DEFINITION = TABULAR
Fp1, l1
Fpn, ln
*CONNECTOR DAMAGE INITIATION, COMPONENT = 1, CRITERION = MOTION
p ,
*CONNECTOR DAMAGE EVOLUTION, TYPE = MOTION, SOFTENING = TABULAR
v,         k
*CONNECTOR STOP, COMPONENT = 1
  a,   b
```

Figure 8 shows a almost perfect compliance between the characteristic of the crash system provided by the supplier and the characteristic which was calculated by means of the connector elements of ABAQUS in the manner described above. In the corresponding absorbed energies versus the time the maximum deviation is less than one percent.

5. Example: Crashscenario 1

Figure 9 shows the whole crash model for the crash scenario 1 according to prEN15227. It consists of two identical locomotives with one 80 tons-freight car per locomotive. These have a vertical offset of 40 mm which is caused in reality by wear of the wheel rim after a certain period of operation. Both trains have an opposite velocity of 18 km/h . The criteria of this scenario are the maximum decelerations and the prevention of climbing of the locomotives.

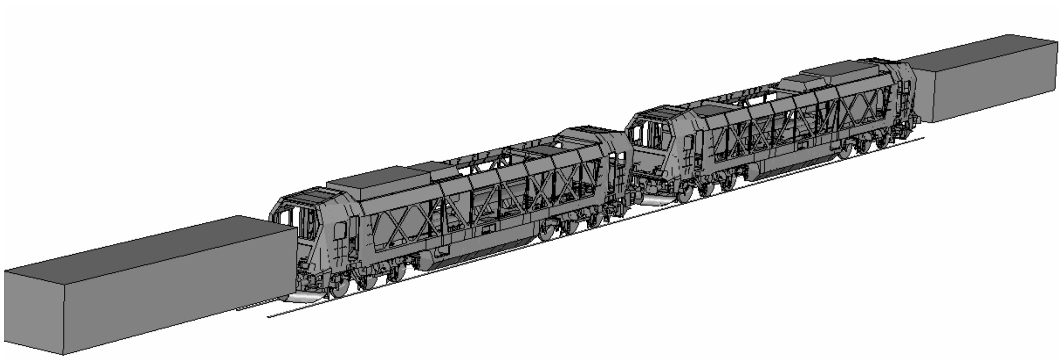

Figure 9. Full scale model of the Crashscenario 1

One major difference to crash simulations in the automotive industry are the very long crash times. Dependent upon the scenarios the crash time amounts up to 300 ms. This is mainly caused by the high kinetic energy due to the mass of the locomotives and the fact that a locomotive acts in case of a crash as a three-mass-oscillator (carbody and two bogies). This leads to a phase shift of the energies of carbody and bogies.

A typical energy characteristic for the whole model is shown in figure 10. During the first 125 ms the correct spring deflection of the primary and secondary suspension is computed, see chapter 4. Then the crash begins and the kinetic energy takes about 275 ms to reach its minimum. The energy due to plastic deformation ALLPD is mainly absorbed by the crashsystem described in chapter 5 and to a small amount by the anti-climbing device. Figure 11 shows the condition of the front end of the locomotive after the crash. The especially designed deformation zones in the underframe of the driver's cab are only slightly activated at this collision speed and their deformation can therefore not be seen. Of great importance is the consideration of a strain rate dependent material law. The Cowper Symons model was used to describe the strain rate dependency, the necessary coefficients have been determined in tests.

The whole crash model consists of about 1,300,000 elements, the overall calculation for 450 ms of real time takes about 53 h. The calculation was performed on a Linux Cluster with four Opteron 256 CPUs engaged, the ABAQUS version was 6-6.1.

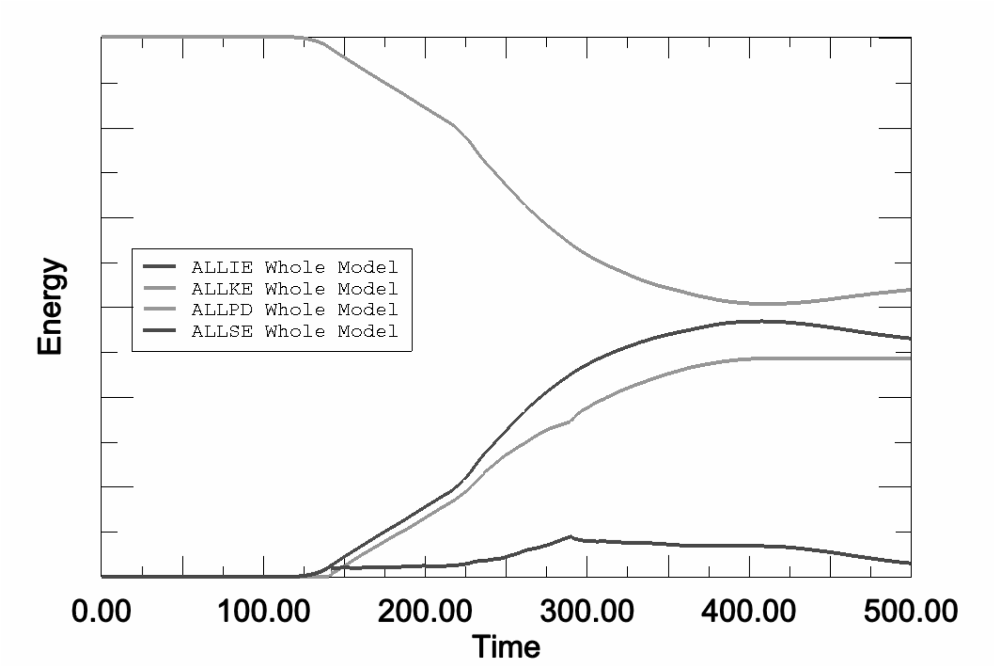

Figure 10. Typical energy characteristics for the crash scenario 1

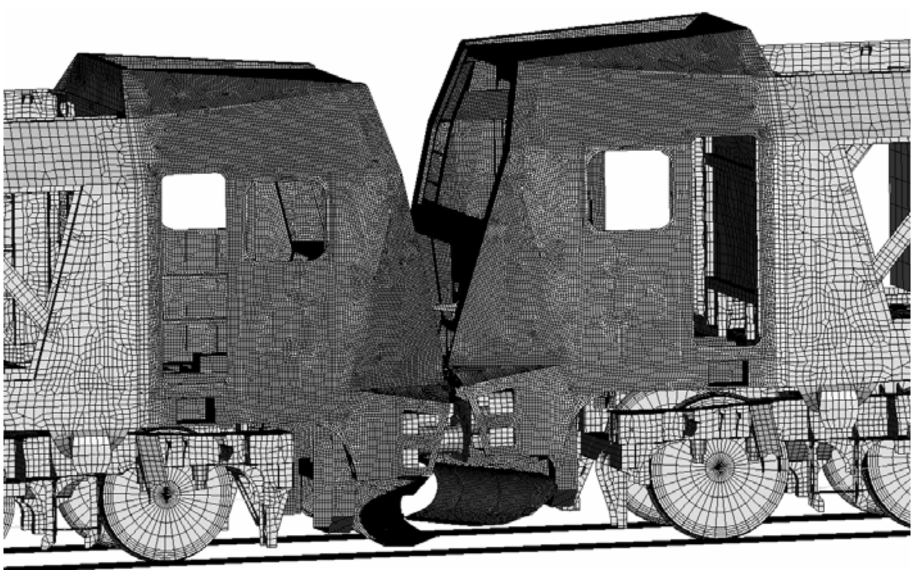

Figure 11. Front end of locomotives after crash

6. Conclusions

Due to the very short development time of only eight month for the carbody of the locomotive MAXIMA®, an efficient and reliable finite element tool for the static and crashworthy design is absolutely necessary. For reasons of cost and time savings this tool should have available an implicit solver as well as an explicit solver so that the static and crashworthy dimensioning can be done with only one FE-model. This also helps to avoid different model versions thus accelerating and improving the development process. Furthermore the explicit solver should be capable to replicate the highly nonlinear elastic-plastic characteristic of the deformations elements. Also a great variety of connector elements should be available for the convenient and correct fixation of all the aggregates, bogies and wheelsets. ABAQUS fulfils all this requirements for the static and crashworthy calculation of railway vehicles and was a crucial factor that we could contribute to the challenging requirement: The first crashworthy locomotive in the weight class of 135 tons.

7. Acknowledgement

We thank the company Voith Turbo Lokomotivtechnik in Kiel for the permission to publish this paper and for the photo of the MAXIMA®.
We also thank the company ESTEisenbahn-Systemtechnik in Wangen, Germany, for the photo and the data of their crash system.

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