Nationaal Lucht- en Ruimtevaartlaboratorium
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Abstract - A computer code has been developed to analyse the impact problem of a light aircraft wing colliding with a frangible approach light structure. This code was evaluated on the basis of a 3-dimensional model, representing such a structure, as produced by the Finish company EXEL. The numerical results were compared to full scale impact test results, provided by EXEL.

The failure mode and the impact peak force were well predicted. As the characteristics of the wing were not available in time (a wing section was unexpectedly made available by Transport Canada), the model was not yet accurate enough to predict the full force history. Hence, it was not possible to generate the impact energy for comparison with the experimental value. This improvement will be carried out in the near future.

The merits of the new simulation capability were clearly shown. The capability provided by the DRI/KRASH code is available on a pc, taking only a few minutes to run. In the near future, the model of the EXEL mast will be improved as indicated above, and the validation of the code will be undertaken, by applying it to a different type of approach light system, made of aluminium.

INTRODUCTION

Certain types of equipment, such as approach light masts and ILS antennas, need to be positioned close to runways at airports because of operational requirements. However, in case of emergencies during take-off or landing, they become obstacles to flight safety. Hence, the requirements for the design of such structures are stringent and seem contradictory: they need to be stiff during operation, and collapse easily during an impact by an aircraft. Such a characteristic is known as "frangible".

The design of frangible structures is not easy, because of the impact dynamics involved. Designers tend to consider the problem as quasi-static. The aviation authorities on the other hand, have difficulty in evaluating the frangibility of structures proposed for installation at airports, and the International Civil Aviation Organisation (ICAO) is presently in the process of defining requirements and specifications. For the case of approach light structures, the current approach to demonstrate the frangibility of a design is by means of a full-scale impact test with a representative light aircraft wing section, at a speed of 140 km/h (Fig. 1).

In order to support the designer, as well as the certifying authorities or their consultants, a computer code is being developed to predict the global behaviour of new approach light designs when hit by the wing of a small aircraft at a relevant speed. This computer code, DRI/KRASH [1,2] was already available to analyse the crashing of aircraft structures and helicopters into the ground. An aircraft model is built up of non-linear beams to represent the stiffness of the aircraft structure, mass points to represent the inertia of the structure, and energy absorbing springs to represent the crushing part of the structure. The characteristics of the springs can be programmed according to test results, which are previously obtained for components.

In order to allow the analysis of the impact of a wing with an approach light structure, it was decided to develop DRI/KRASH in such a way, that both the aircraft wing and the approach light structure can be combined in a single model. The latest version of DRI/KRASH, as developed specifically within the context of this project by DRI, contains a new option, which allows the specification of different initial velocities for each of the individual masses. This feature, along with many other improvements, extends the capability of the program to enable the modelling of the coupled interaction between a moving mass system (aircraft) and a stationary structural system (approach light structure). Both systems can now be modelled with the beams, masses and springs available in KRASH.

The project to develop the computer code contains four phases: a feasibility phase, a development phase, a validation phase and a phase to develop design criteria. The first two phases were completed with a midterm review and an update of the work programme. In a previous paper, the results of the feasibility phase were presented [3]. A comparison was made of the numerical results obtained with a preliminary model with full-scale test results, generated with the commercially available frangible approach light structure of EXEL [4,5]. EXEL is a Finish company, and has meanwhile supplied Amsterdam Airport with frangible approach light systems. Since then, structural tests were carried out on sections of the EXEL mast [6], to generate failure criteria. Also, compression tests were carried out on the wing impactors used in the tests, to establish their characteristics [7]. The wing impactors were made available by Transport Canada, which participates in ICAO's Frangible Aids Study Group (FASG) with tests and computations.

The present report gives the final results of the development phase, in the form of an improved model to simulate the impact of EXEL's frangible approach light structure by an aircraft wing section. Validation of the computer code will be carried out by modeling approach light structures of other manufacturers, for instance of the metal structures tested by Transport Canada.

EXEL TEST RESULTS

The impact test programme on six EXEL approach light masts implied the impact at 140 km/h by a wing section (Fig. 2), representative of a light aircraft (as specified by the FASG), which was mounted on a truck. Forces, accelerations and the velocity of the truck were measured, and high-speed video images were obtained.

The masts were approximately 6 m tall, and contained a dummy top mass of 15 kg, representative of three lights and the cross bar on which they are mounted. The masts are configured as a composite lattice structure (made of glass-fibre polyester) with a square cross section of 400 mm x 400 mm, consisting of four vertical tubes, mounted on a steel bracket, and connected with diagonal tubes made of fiber-glass reinfored plastic. The masts were impacted at a height of 4.1 m above the ground.

Impact forces were measured with two load cells, which were located between the wing backing column and the cantilever beam of the support structure (and filtered with a 1 kHz low pass filter), see figure 2. The total force was calculated as the sum of the two indications. The absolute maximum force during the impact was determined to be the peak force. Vertical and horizontal accelerations were measured also, to determine the relative motion between the support structure and the truck, but this information was less significant. The velocity of the truck was measured by a pulse counter, which was mounted on the drive shaft of the truck.

The impact energy was determined by integrating the impact force with the forward displacement of the impactor. This displacement was calculated from the recorded pulse count versus time relationship. The correction, taking into account the movement of the impactor relative to the truck body, was calculated by using the horizontal acceleration measured by the accelerometer.

The contact time was determined on the basis of the energy versus time curve. The rise time from the zero energy level to the maximum energy level was determined to be the contact time.

Two natural frequencies were established: 184 Hz, the local resonance frequency of the impactor, and 6.3 Hz, the global resonance frequency of the whole system.

The first three impact tests carried out by EXEL were representative of the conditions as modelled with KRASH. The other three tests were more complicated, with lighting cables connected. The average results of the first three tests were: peak force 23.9 kN, impact energy 36.7 kNm, and contact time 104 ms.

DRI/KRASH MODEL

The feasibility phase resulted in the development of a preliminary model [3]. The model was 2-dimensional, based on general structural properties. The "frangibility" option (a moving wing section impacting a stationary approach light structure) was shown to act properly. Recommendations for improvement were made as follows:

- Create a 3-dimensional model of the mast.
- Incorporate structural failure criteria for the mast.
- Refine crushing properties of the wing section.
- Adjust the point of contact.
- Update mass and stiffness properties of the mast.
- Compare the overall deflection mode with test data.
- Compare the force and energy levels with test data.
- Compare the deformation and failure modes with test results.

In the current study, attention was paid to these recommendations. The preliminary model was extended to a 3-dimensional model as depicted in figures 3-4. In the preliminary model, the ‘moving’ wing was modelled with three beams and three masses, representing, the truck which moves the wing section, the wing backing column (steel beam) on which the wing was mounted, and the wing itself, respectively. In the current model, the ‘moving’ wing is represented by two parallel series of three beams and three masses, each with half the stiffness and half the mass properties. In each series of three beams, the beam representing the wing section has non-linear stiffness behaviour and has been tuned with results from the EXEL tests [5]. At the time that the current study was carried out, the characteristics obtained from the static compression tests on the wing, performed at NLR [7], were not yet available.

The wing model is connected with both the two vertical front tubes and the two vertical aft tubes. The stiffness of the beams, which represent the connection between the wing and the two aft tubes, becomes ‘active’ when the front tubes are deformed in such a way that they ‘make contact’ with the aft tubes.

The top crossbar with three lights is represented by a lateral beam, which connects the two frame halves in the XZ-plane with each other, as depicted in figure 4. The total top mass of 15 kg, representing the lights and the cross bar, is equally distributed over both end-nodes of this beam.

For a better agreement with the actual test, the height at which in the 3-dimensional model the wing impacts the mast has been reduced with respect to the preliminary model, which was thought to be more in accordance with the test case at the time. Further, the boundary conditions of the ‘moving’ wing were modified in such a way, that the wing remains on the same height (as in the actual test) during the whole analysis (by increasing the bending stiffness). So, the wing can only deform in the longitudinal direction.

Measured failure criteria [6] were incorporated in the model for all beams. From several preliminary analyses with the 3-dimensional model it was observed that beams failed rather early in bending, which means that these beam were completely ‘removed’ in the analyses. The experimental results indicate, that after bending failure, the tubes still absorb energy due to their remaining axial stiffness. To be able to take this into account in the model, the affected beams were replaced with two beams, i.e., one which will fail in bending and one which will fail in axial tension or compression. These beams are located near the foundation of the mast, the connection with the wing and the connection with the masses of the landing lights at the top. In figures 3-4, these beams are indicated by the lines between the ‘open nodes’.

The model consists of 106 masses and 205 beams, including 2 non-linear beams (wing model) and 24 ‘double beams’ (to allow failure due to bending and due to tension/compression, separately).

ANALYSIS

The response of the approach light structure, due to an impact of the moving wing at an initial velocity of 38.9 m/s (= 140 km/h), was analysed. This was simulated by the application of an initial velocity of 38.9 m/s on the nodes, which represent the truck, the wing backing steel beam, and the wing, respectively. The duration of the simulation was 40 milliseconds, with a time integration step size of 5.0 microseconds. This duration captures the phase in which most of the damage to the wing section takes place.

Figure 5 shows the actual deformation mode as observed in test 1. The front vertical tubes cut through the wing nose, until they hit the wing spar. Subsequently, the mast moves with the wing, while the top and bottom of the mast remain in place. Finally, the aft vertical tubes failed in tension at their foundation, but this happens at a later stage. In figure 6, the simulation of the impact at several time steps up to 40 ms is presented, which shows a close resemblance with the test results. Figure 7 shows, that the failure mode is not symmetrical, possibly due to the unsymmetrical layout of the diagonal tubes.

Figure 8 shows the velocity of several mass points. The mass points 103 and 106 represent the wing section, and start with an initial velocity of 40 m/s. This velocity reduces to 30 m/s, while in the end, the mass points will have to move with the truck, at an undisturbed 40 m/s. This point was not yet reached in the simulation. Mass point 23, representing (one half of) the top mass, remains in place during the first 40 ms, like in the actual test (Fig. 5). Mass point 18, just above the impact point, gradually picks up speed.

Figure 9 shows the forces in several beams. Beams 173 and 176 each represent one half of the truck. Beams 174 and 177 each represent one half of the backing beam, and beams 175 and 178 each represent one half of the wing section. The forces in the wing backing beam are thought to be most representative of the forces recorded in the test. These forces are added, and the sum is represented in figure 10. Also in figure 10, the test results are shown, and compared to the numerical results. It is clear that the first two peak forces coincide well with the experimental values, and also the maximum value is well predicted: 24 kN. The subsequent force history is less well predicted, but can be improved in the future, by using the characteristics of the wing impactor, as mentioned in chapter 3. In this respect, it was not yet relevant to try to predict the impact energy, for comparison with the experimental value.

CONCLUSIONS

A computer code has been developed to analyse the impact problem of a light aircraft wing with a frangible approach light structure. Hereto, the DRI/KRASH code was made available in an extended form by DRI, according to the specifications of NLR. Subsequently, a simplified 2-dimensional model was analysed, to confirm the feasibility of this approach. In the present paper, an improved 3-dimensional model was evaluated, which contained the characteristics of the benchmark problem: full scale test results provided by the Finish company EXEL. The important parameters to be evaluated are the failure mode, the peak impact force, and the impact energy.

The result of this evaluation was successful, in so far that the prediction of the failure mode and the peak impact force were correct. As the characteristics of the wing impactor were not available in time (the impactor was unexpectedly made available by Transport Canada), the model was not yet accurate enough to predict the full force history. Hence, it was not possible to generate the impact energy for comparison with the experimental value. This improvement will be carried out in the near future.

The merits of the new simulation capability were clearly shown. One approach to simulate this impact phenomenon would have been to use an explicit finite element code, such as PAM-CRASH [8]. However, a model for such a generic finite element analysis approach might typically contain 50,000 degrees of freedom, which needs to be analysed for a large number of time steps, typically 10,000. This capability is technically out of reach of the designers of frangible approach masts, and very expensive to use for other interested parties.

On the other hand, the hybrid capability provided by the DRI/KRASH code, as demonstrated here, is available on a pc, taking only a few minutes to run. However, a KRASH-model consists of large elements of the size of full components, and requires test results for these components as input. As manufacturers usually perform component tests anyway during the design process, this effort should not be prohibitive.

In the near future, the DRI/KRASH model of the EXEL mast will be improved as indicated above, and the validation of the code will be undertaken, by applying it to a different type of approach light system, made of aluminium.

ADDITIONAL RESULTS

Since the first issue of the present report, additional numerical results were obtained. These results were presented at the 3rd KRASH user's seminar, January 8-10 2001, Arizona State University, Tempe, Arizona, USA.

The results consist of an improved simulation of the impact event, in terms of peak force and absorbed energy. The results are presented in figures 11-12, and show good agreement for the first 70 % of the impact duration.

ACKNOWLEDGEMENT

The authors are pleased to acknowledge that the work herein was supported by the RLD (Netherlands Department of Civil Aviation), monitored by Mr. A.L. Franssen. They are also grateful to EXEL Oy for making available the results of the full scale impact tests on their masts, and to Transport Canada to supply wing impactors for testing at NLR.

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a) Wing impactor mounted on truck   b) Full scale impact at 140 km/h

c) Wing impactor after the test

Figure 1 Full scale impact test on frangible approach light structure

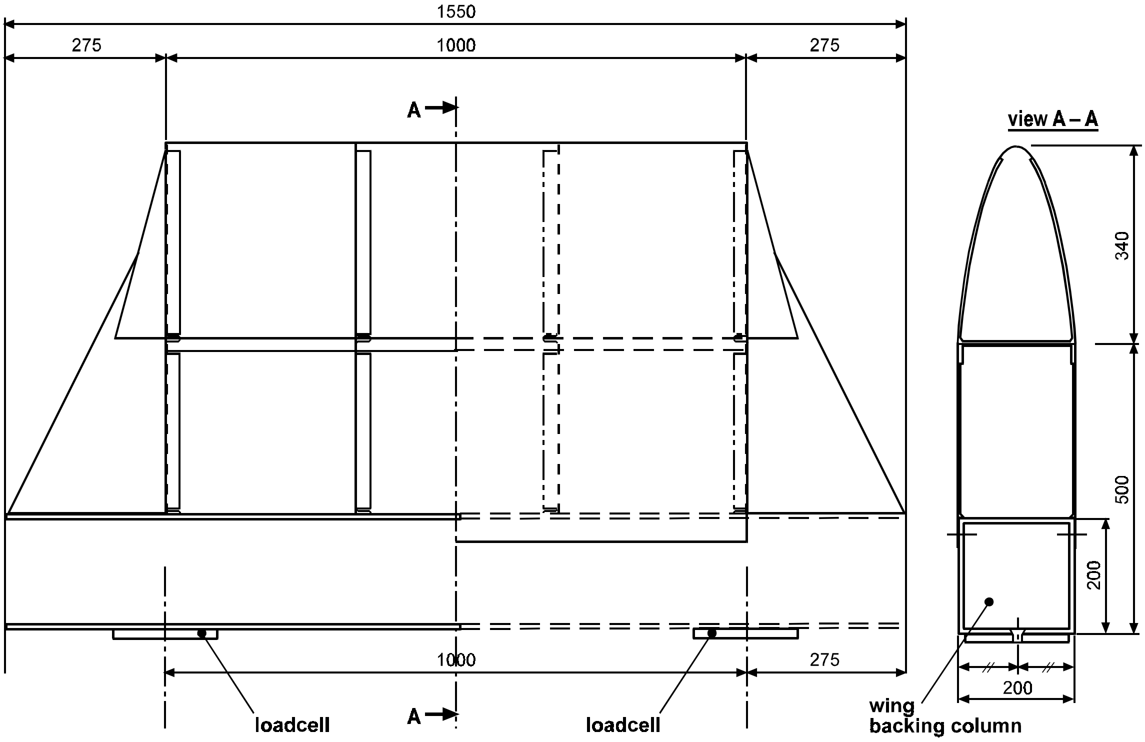
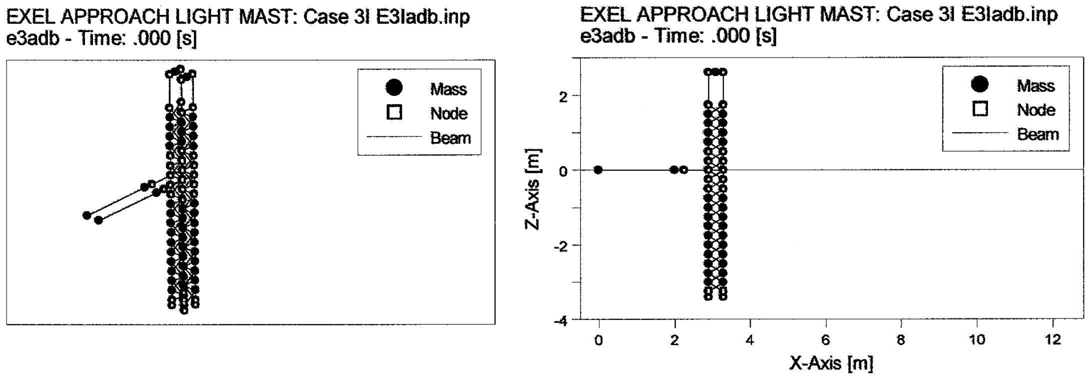
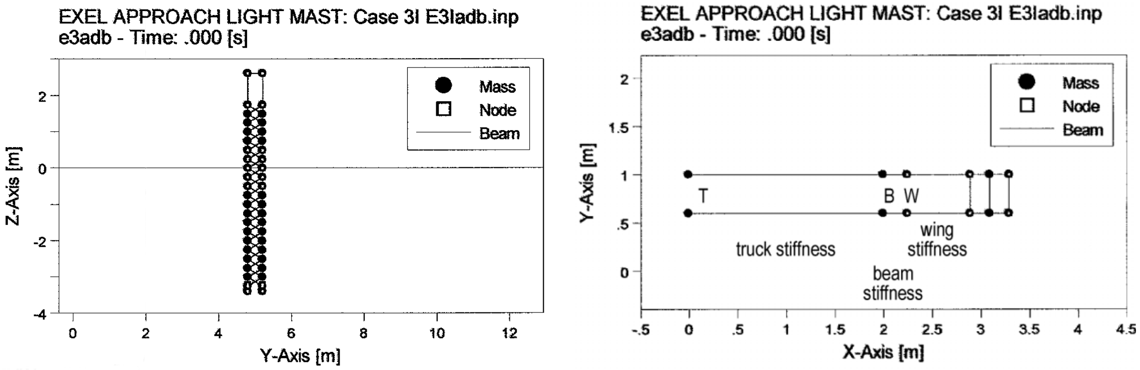


Figure 2 Wing impactor and load cells



a) Perspective b) Side view



c) Frontal view d) Top view

Figure 3 Different views of the impactor/mast model

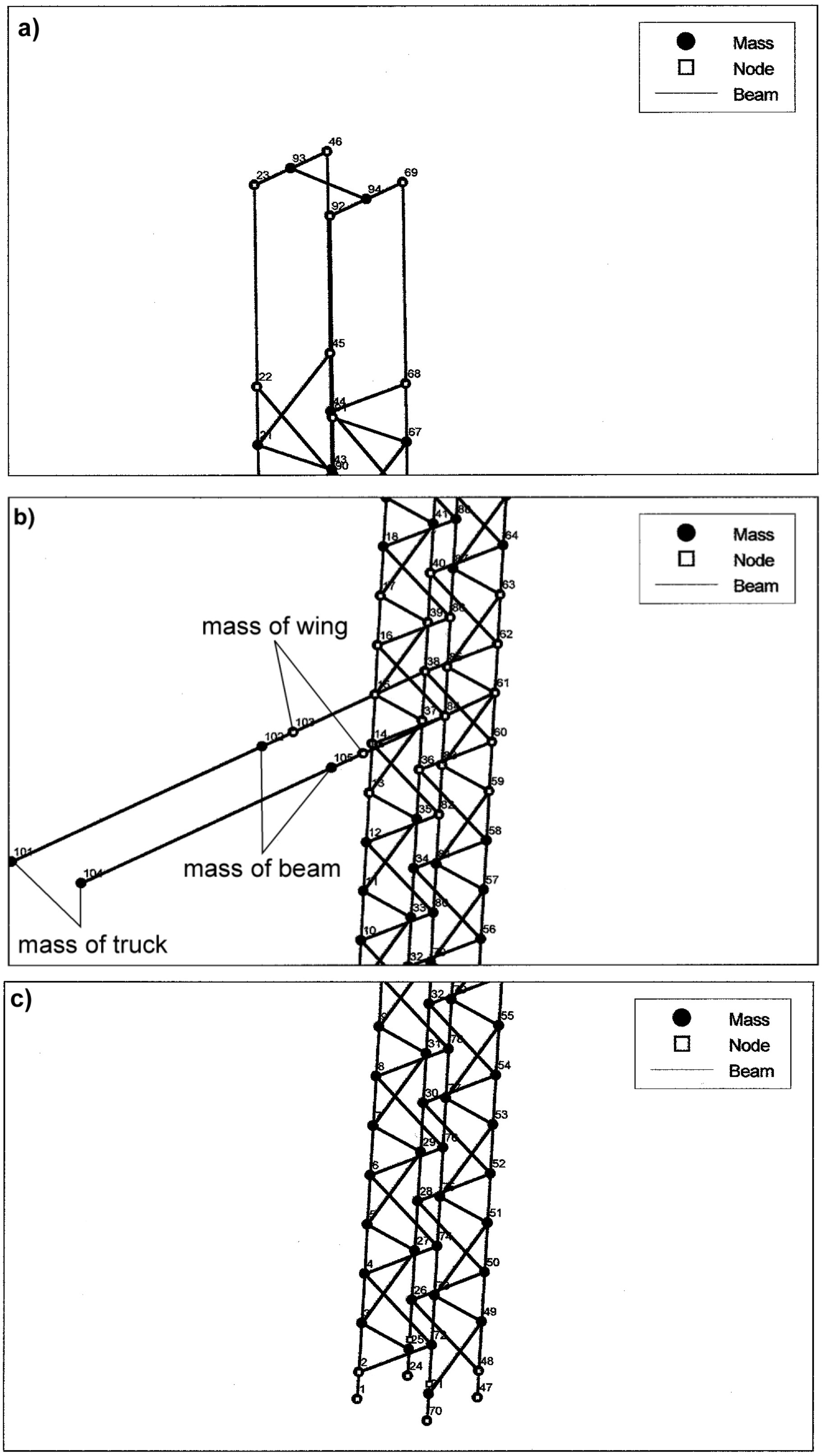


Figure 4 Details of model

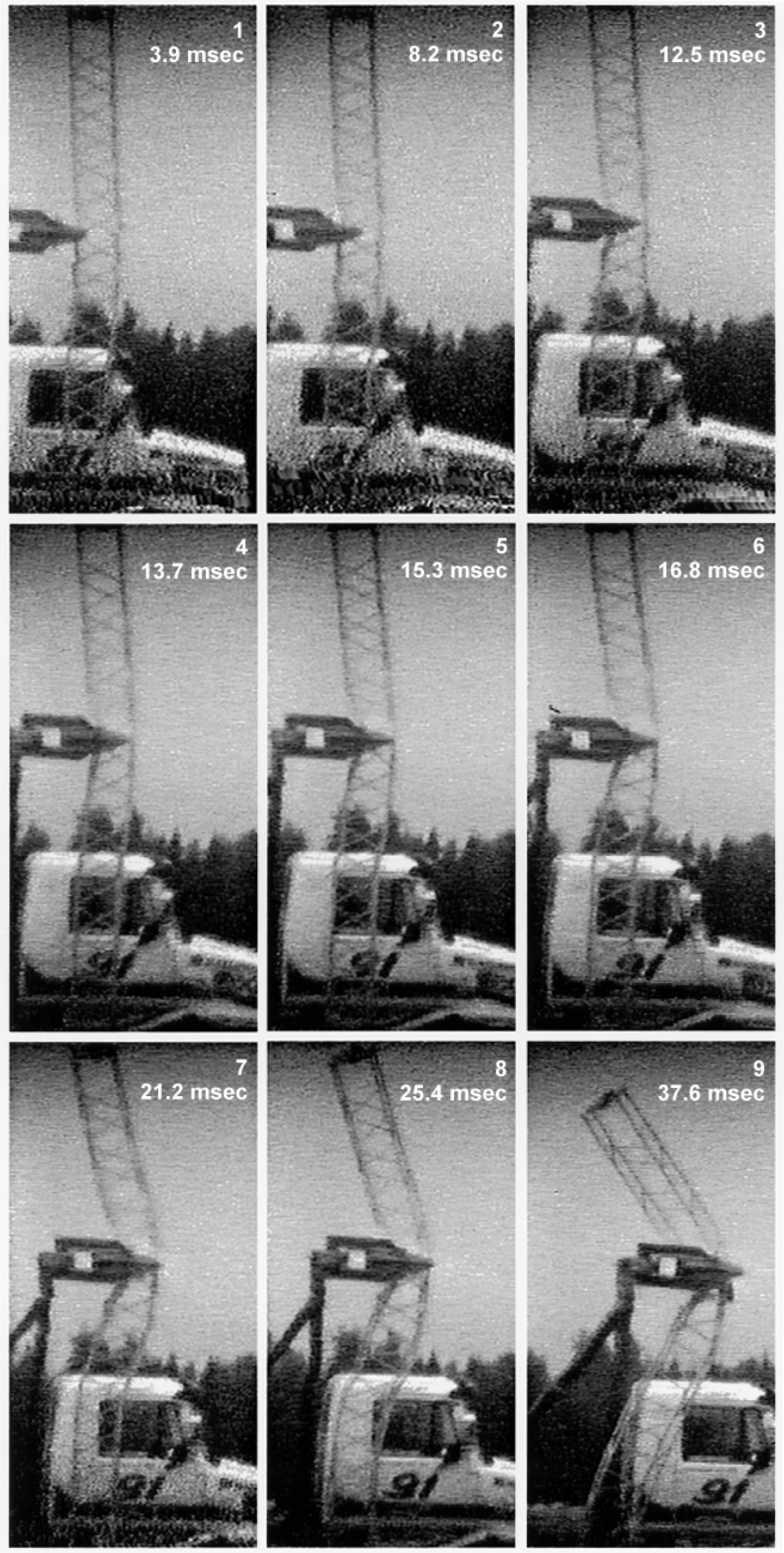


Figure 5 Photographic sequence of the impacted mast from EXEL mast test 1

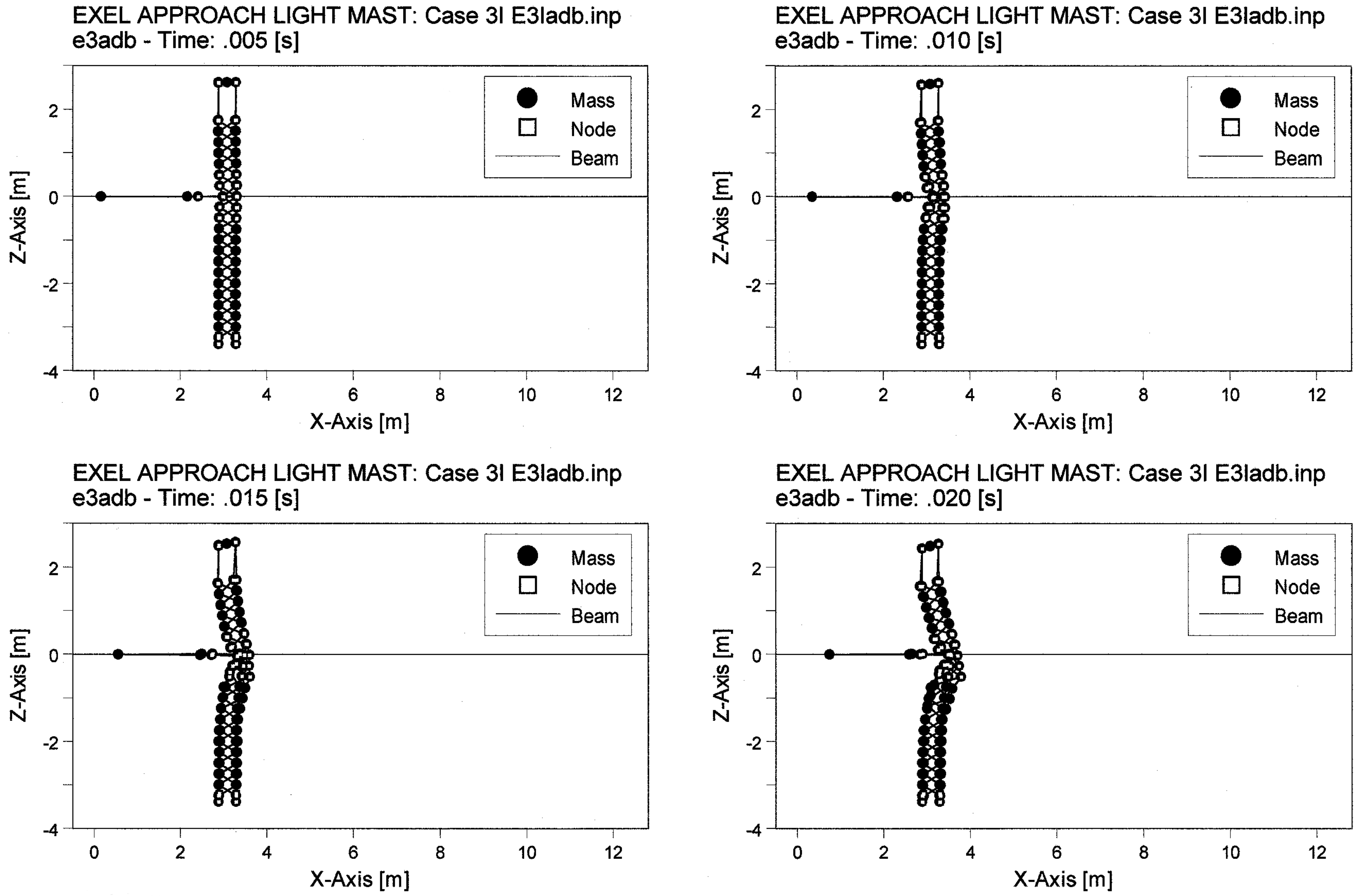
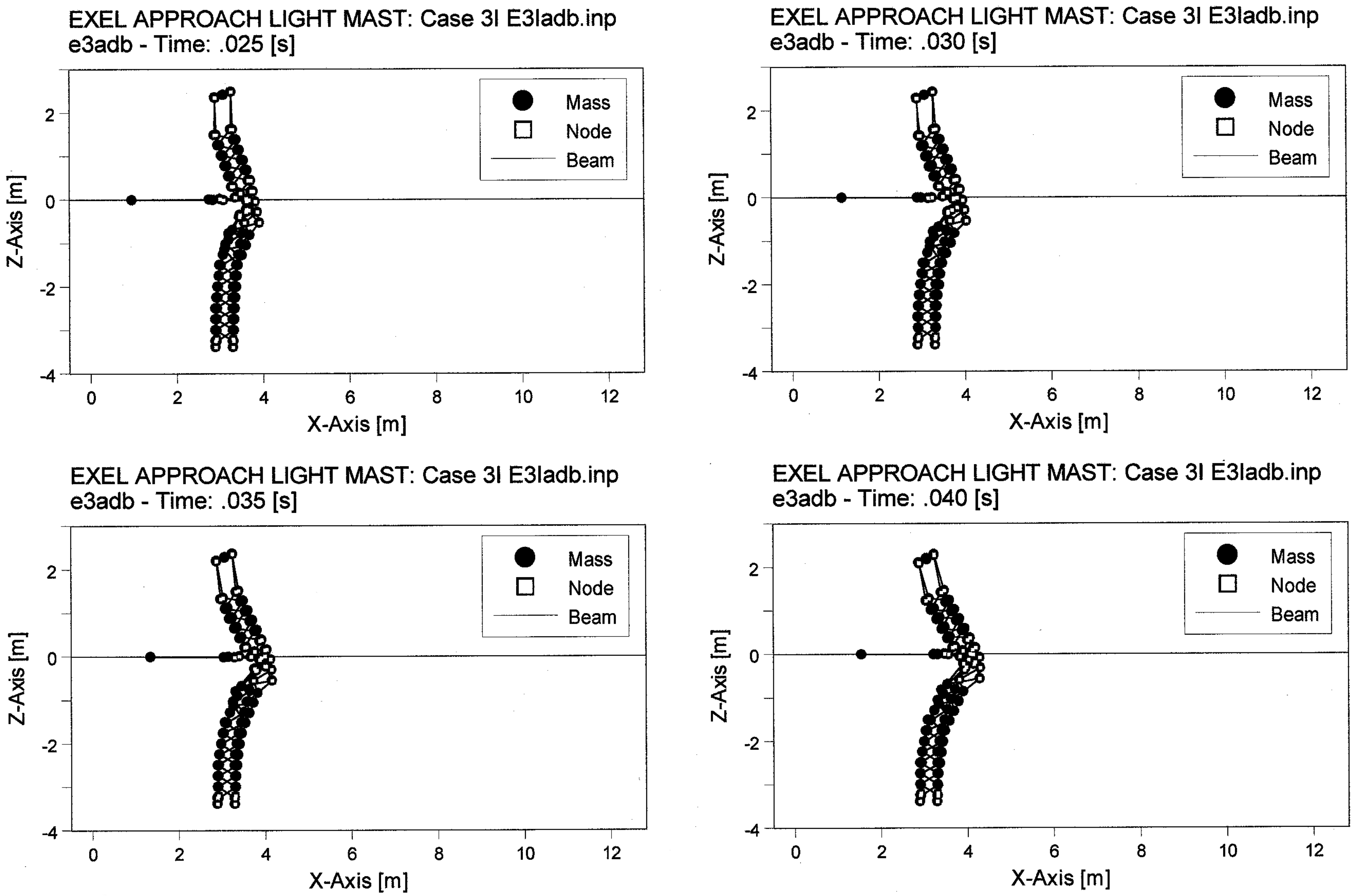


Figure 6 Deformation of the mast, computed with KRASH



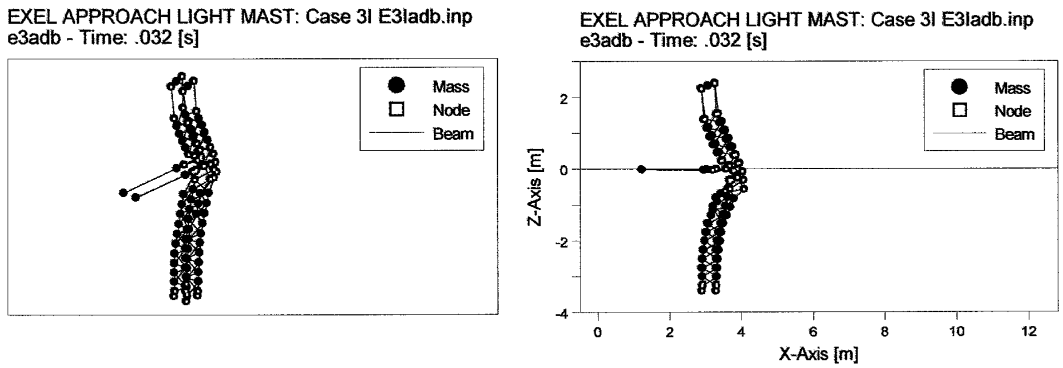
EXEL APPROACH LIGHT MAST: Case 3I E3Iadb.inp
e3adb - Time: .025 [s]

EXEL APPROACH LIGHT MAST: Case 3I E3Iadb.inp
e3adb - Time: .030 [s]

EXEL APPROACH LIGHT MAST: Case 3I E3Iadb.inp
e3adb - Time: .035 [s]

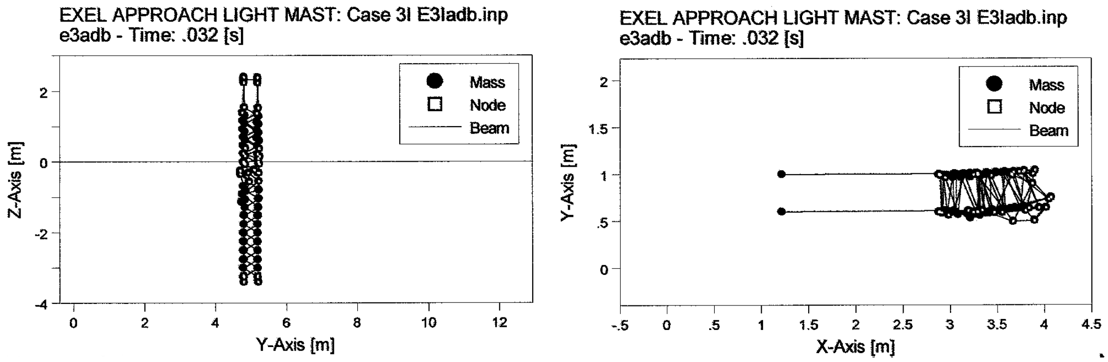
EXEL APPROACH LIGHT MAST: Case 3I E3Iadb.inp
e3adb - Time: .040 [s]

Figure 6 Deformation of the mast, computer with KRASH (continued)



a) Perspective

b) Side view



c) Frontal view

d) Top view

Figure 7 Deformation of the mast from different views

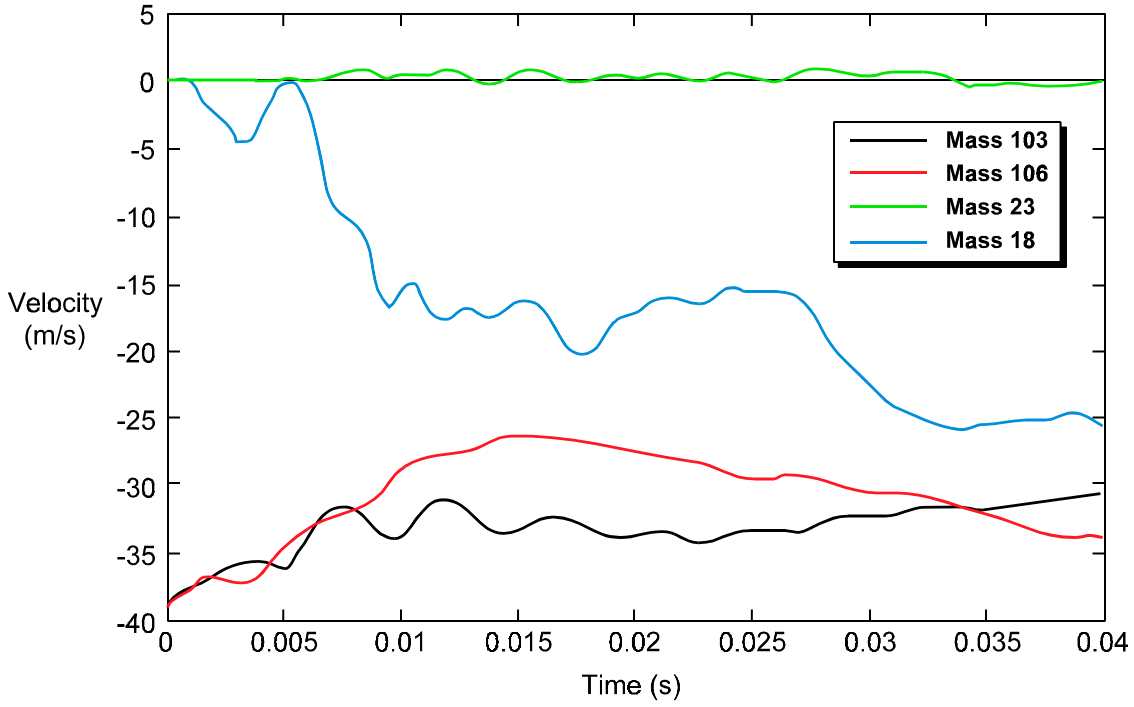
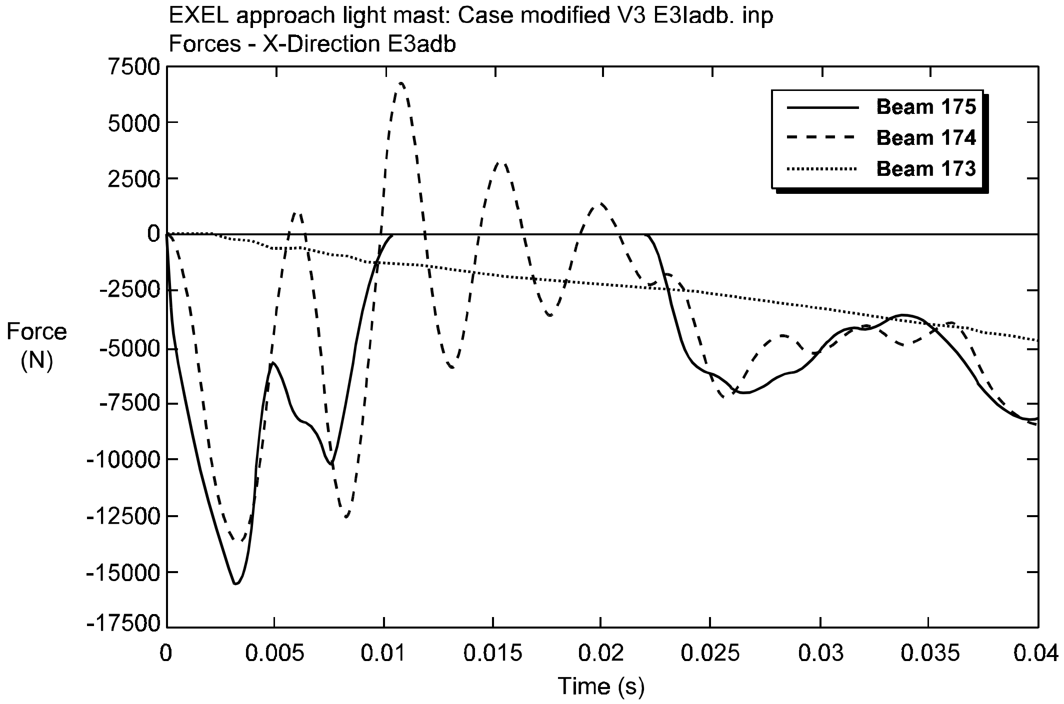
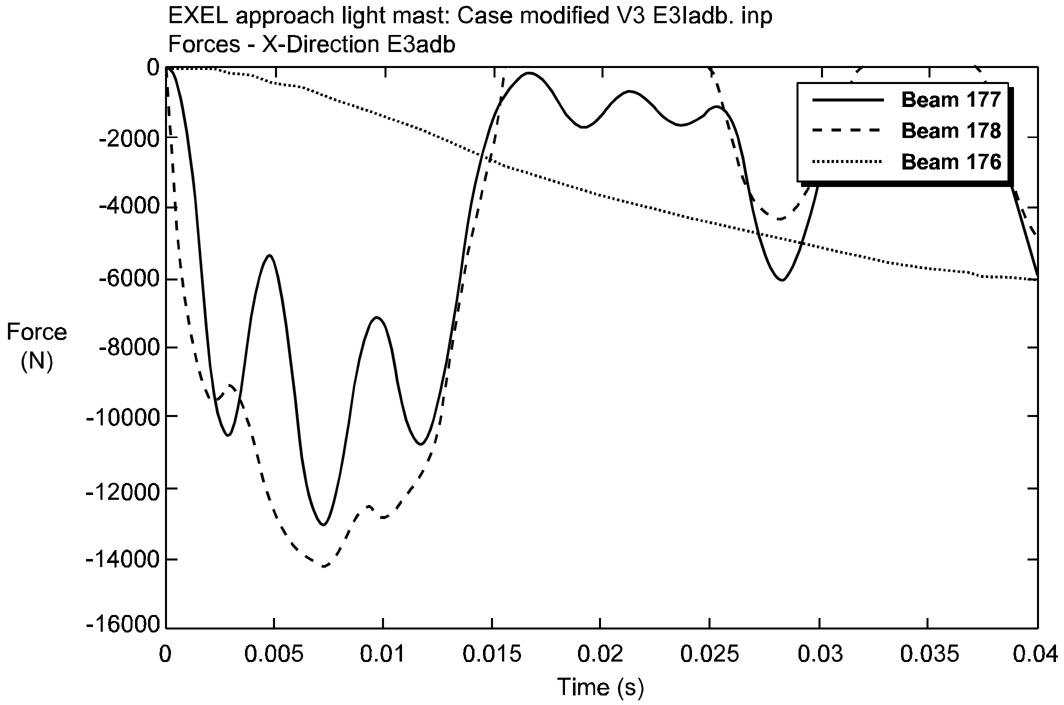


Figure 8 Velocity of mass points

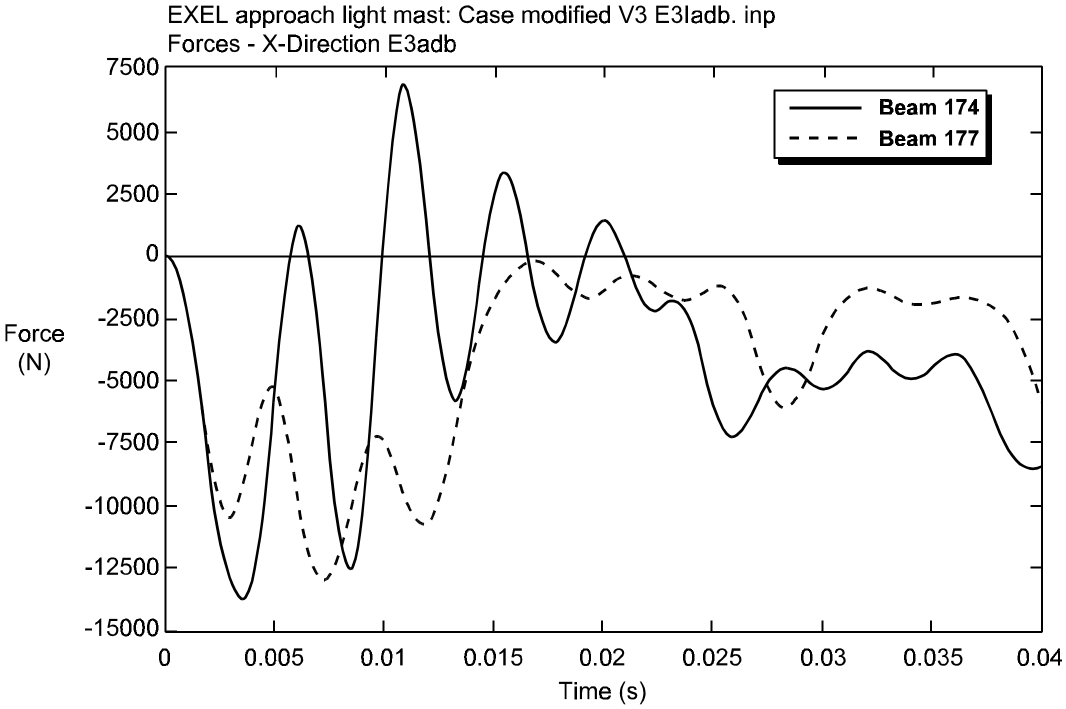


a) Beam 173 = truck, beam 174 = beam, beam 175 = wing



b) Beam 176 = truck, beam 177 = beam, beam 178 = wing

Figure 9 **Force versus time plots for the beams representing the truck, the wing backing beam and the wing section**



c) Forces in the wing backing beam

Figure 9 Force versus time plots for te beams representing the truck, the wing backing beam and the wing section (continued)

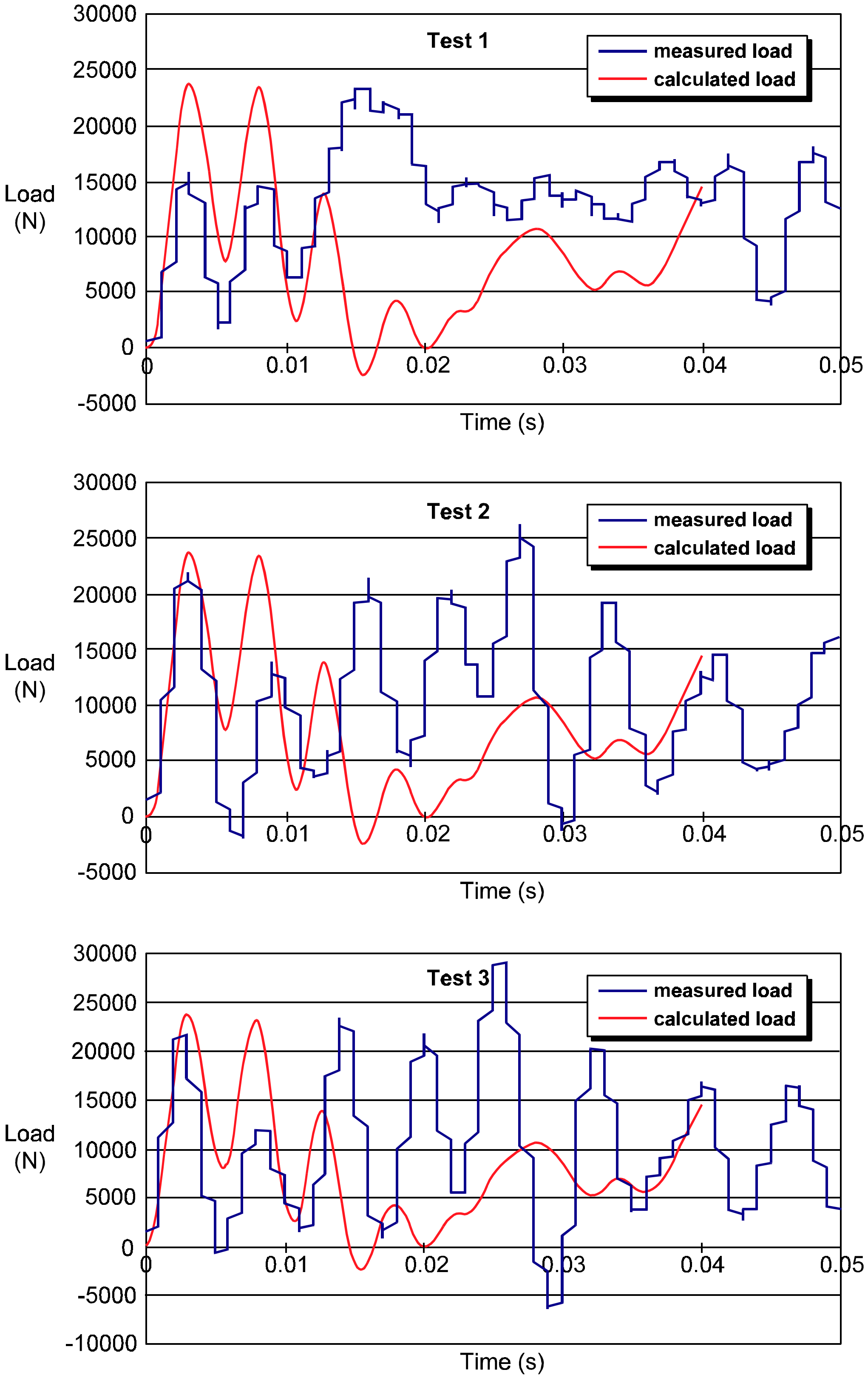


Figure 10 Comparison of impact forces determinated by tests and analysis

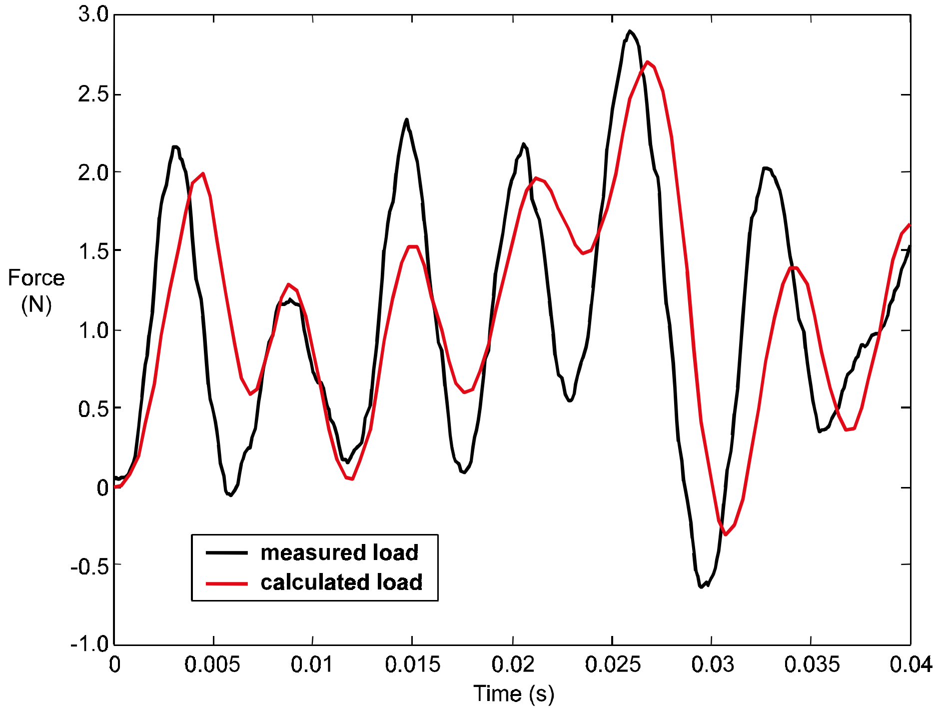


Figure 11 Force versus time

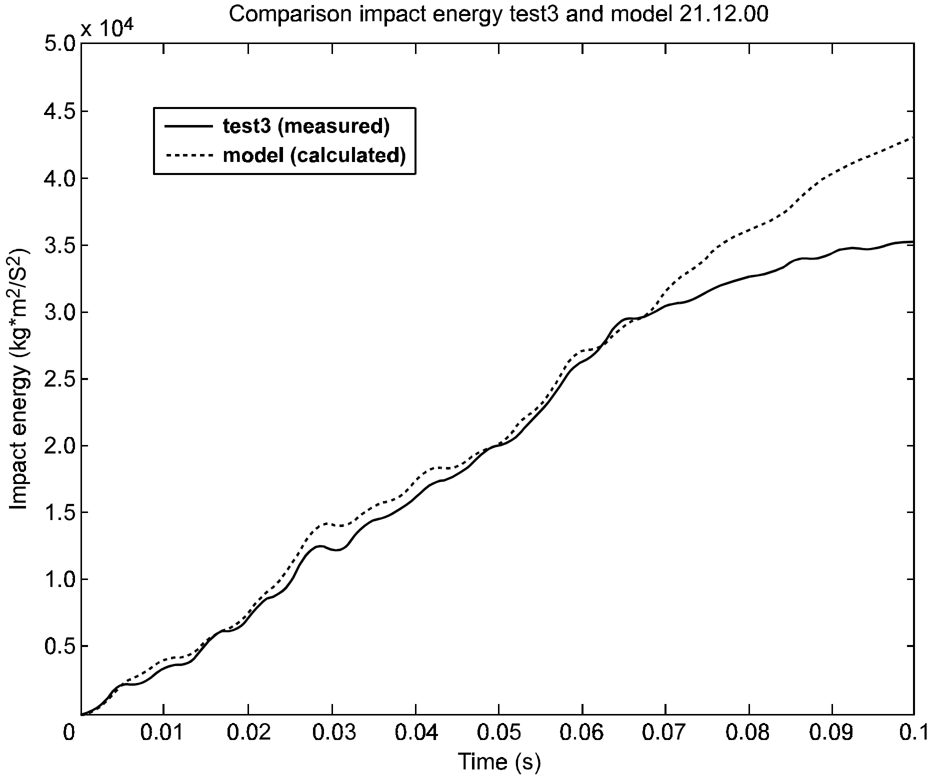


Figure 12 Impact energy versus time