

Studies of Medium Scale Non-axisymmetric Missile Impacts

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1 ABSTRACT

Protective structures can be considered to be in risk of missile impact. In many cases it is not possible to create a detailed nonlinear model of the impact or carry out experimental testing in full scale. VTT Technical Research Centre of Finland has built the IMPACT test facility to investigate the impact of hard and deformable missiles on rigid and deformable targets.

This experimental testing apparatus is used to provide data of various impact scenarios and validate impact models. Experimental data of different shaped missile impacts against concrete walls is scarcely available in literature. The current impact tests are medium scale. Due to nonlinearities, the impact phenomenon is strongly dependent on scale. It is discussed in the paper if the current calculation methods and test results can be used to make assumptions of impacts in different scales.

An example of the experimental testing carried out is presented in the paper. In this test a missile with wings is impacted against a rigid-like steel target. Experimentally measured data is presented and compared against impact models. The calculations give reasonable approximations of the studied impact scenario but they must be further validated before they can be applied to other impact scenarios.

2 INTRODUCTION

Impact loads have been a design consideration for protective structures since the 1960's. Besides the damage caused by impact to the protective structure itself, one concern in structural design is to prevent the missile or one of its components from penetrating the protective structure. Also, if the protective structure remains intact but the impacting missile contains liquid, liquid spreading outside the structure must be considered. In many cases it is not possible to create a full nonlinear model of impact and simpler evaluation methods and small scale experimental testing is needed. In order to make simplifications reliably, the impact phenomenon in multiple scales must be known in as much detail as possible. Experimental data of simple missile impacts against concrete walls are available in literature but tests carried out using complex non-axisymmetric missiles with water included are not available.

VTT Technical Research Centre of Finland has studied medium scale missile impacts against rigid and deformable targets to provide data for the calibration and verification of numerical models of impact. Missiles used in most of the tests have been cylindrical aluminium and steel pipes. Recent development in the testing is tests with a more structurally complex non-axisymmetric missile that can include water. The objective of these tests is to produce a non-uniform impact loading transient with a changing loading area over the duration of the impact. The goal is to predict the results of the experiments using a mathematical model and if successful, apply the same methods to other impact scenarios. Due to nonlinearities, the impact phenomenon is strongly dependent on scale. Therefore the effect of scale must be known so that one can reliably utilize the methods that have been verified using medium scale data to larger scale impact scenarios or directly scale the results.

3 METHODS EMPLOYED IN THE WORK

Numerical results presented later in the paper are obtained using two different methods. First Riera's method for determining impact loads for deformable missiles is utilized. Also, the impact is simulated in detail using finite element method with explicit time integration.

Riera's method introduced in Riera (1968) and discussed by Abbas et al. (1995) can predict the behaviour of deformable missile impacting against a rigid and stationary target. Riera's method can be cast in to the form of a set of partial differential equations with initial conditions (1). Below $M(t)$ is missile mass, $\mu(x)$ is missile mass distribution, $V(t)$ is missile velocity, $P_c(x)$ is missile crushing force and x is a coordinate of the section currently in contact with the target. Overdot is used to denote the time derivative. M_0 , L_0 and V_0 are the initial values for missile mass, length and velocity, respectively.

$$\begin{aligned} \dot{M}(t) &= -\mu[x(t)] \cdot V(t), & M(0) &= M_0, & M(t) &\geq 0 \\ \dot{V}(t) &= \frac{-P_c[x(t)]}{M(t)}, & V(0) &= V_0, & V(t) &\geq 0 \\ \dot{x}(t) &= V(t), & x(0) &= 0, & x(t) &\leq L_0 \end{aligned} \quad (1)$$

After solving the equation set above impact force is obtained as:

$$F(t) = P_c[x(t)] + \mu[x(t)] \cdot [V(t)]^2 \quad (2)$$

The deformation mode for cylindrical missiles found in the experiments corresponds to a folding mode given by Jones (1989). The mode is depicted in Figure 1.

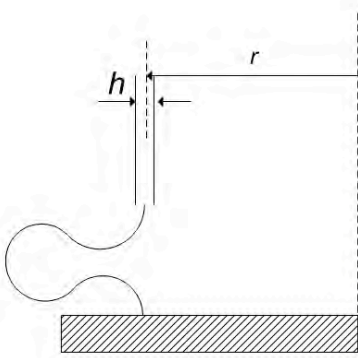


Figure 1. Missile pipe folding mode assumed for the pipe. Redrawn from (Jones 1989).

As given by Jones (1989), the crushing force for this folding shape is

$$P_c = \frac{2\pi^{\frac{3}{2}}}{3^{\frac{1}{4}} \left[0.86 - 0.37 \sqrt{\frac{h}{r}} \right]} \sigma_y h \sqrt{hr} \quad (3)$$

Missile crushing in impact is a very fast dynamic event lasting only milliseconds. As strain rates increase, many materials show an increase in their yield strength. For aluminium alloys, which is the primary material used in the missiles, the effect of strain rate is small but is still considered here. The influence of strain rate sensitivity is taken into account using the viscoplastic Cowper-Symonds constitutive model for uniaxial compression (Jones 1989). The relation between the dynamic and static yield strengths is

$$\frac{\sigma_{y,dyn}}{\sigma_{y,stat}} = 1 + \left(\frac{\dot{\epsilon}}{D} \right)^{\frac{1}{q}} \quad (4)$$

For aluminium alloys the parameters are $D=6500 \text{ s}^{-1}$ and $q=4$ and parameters for steel are $D=40 \text{ s}^{-1}$ and $q=5$, as given by Jones (1989).

Numerical analysis of missile impact is presented in the later sections. This analysis has been carried out using commercial finite element software Abaqus/Explicit. Explicit dynamic analyses are computationally efficient for the analysis of large models with short dynamic response times and for the analysis of extremely discontinuous events or processes. Also an efficient general contact procedure is readily available. Explicit methods in Abaqus finite element program are based on the explicit central difference time integration rule and the use of diagonalized mass matrices. The procedure is very common in structural analyses and more details of the procedure can be found in the Abaqus documentation (Abaqus 2007).

4 SMALL SCALE CONSIDERATIONS

The testing apparatus described briefly later and in more detail by Lastunen et al. (2007) is designed to carry out medium scale impact tests. In the current context, medium scale stands for typical missile and target dimension of 1-2 metres. Although the experimental tests are not designed to be small scale models, scale considerations are needed in order to determine if the results obtained are usable when considering other scales of similar impacts. Dimensional analysis using Buckingham's π -theorem is used to obtain the scaling laws. In general, the requirement for model testing is to obtain equality in the dimensionless groups, or π -terms, for the small scale model and the full scale structure.

Jones (1989) provides the general dimensionless terms for impact problems. In this work the impact is studied using Riera's method and dimensionless groups for this problem are given by Kuutti (2007). It is assumed that similitude is maintained, i.e. the proportional geometry of the missile is identical and same construction material is used in all scales. It is found that the following dimensionless terms should be equal in all scales:

$$\pi_1 = \frac{L_0 \rho A}{M_0}, \pi_2 = \frac{\sigma_y}{\rho V_0^2}, \pi_3 = \frac{r}{h}, \pi_4 = \frac{V_0}{L_0 D} \text{ and } \pi_5 = q. \quad (5)$$

From these terms it can be determined that most of the dimensionless groups are equal for example in the case of geometric scaling where the two models have similar mass distribution, geometrical cross section properties and material properties, i.e. density ρ and yield strength σ_y . Also it is required that the crushing force, P_c , is scalable by the dimensionless groups.

The problems with geometric scaling in strain-rate sensitive structures can be seen from dimensionless groups π_2 and π_4 . Using same material dictates that the impact velocity must be equal as seen in dimensionless group π_2 . If the velocity is equal, term π_4 gives that the product $L_0 D$ must be equal. As D is material constant and thus equal in the two cases, term π_4 is only equal if $(L_0)_{full} = (L_0)_{model}$ indicating no scaling.

An example of the effect of strain rate can be seen when considering the impact of a cylindrical missile against a rigid-like target in three scales using geometrically similar scaling. The base scale is selected so that it represents the typical dimensions of the experimental tests carried out in the current project. Missile length in this scale is 1 metre. The scaling factors considered now are 1/15 and 1/30. All dimensions are scaled with factor λ and masses with factor λ^3 . Velocities are independent of the geometric scale factor λ . Missile lengths considered are thus 1, 15 and 30 metres. Details of the studied impact scenarios are given in Table 1. In addition to the properties listed in Table 1, similar material is assumed for all the missiles. Required material properties are $\rho=2700 \text{ kg/m}^3$, $\sigma_y=255 \text{ MPa}$ and strain rate effect parameters are $D=6500 \text{ s}^{-1}$ and $q=4$.

Table 1. Missile properties in different scales.

Missile property	Geometric Scale		
	$\beta = 1$	$\beta = \frac{1}{15}$	$\beta = \frac{1}{30}$
Diameter (mm)	200	3000	6000
Wall thickness (mm)	5	75	150
Length (m)	1	15	30
Total mass (kg)	15	50 625	405 000
Impact velocity (m/s)	150	150	15

Solving numerically the equation set (1) for all three scales and calculating the impact forces yields to force curves and missile crushing shown in Figure 2. The results are scaled using dimensionless groups given in (5) so that the results are comparable.

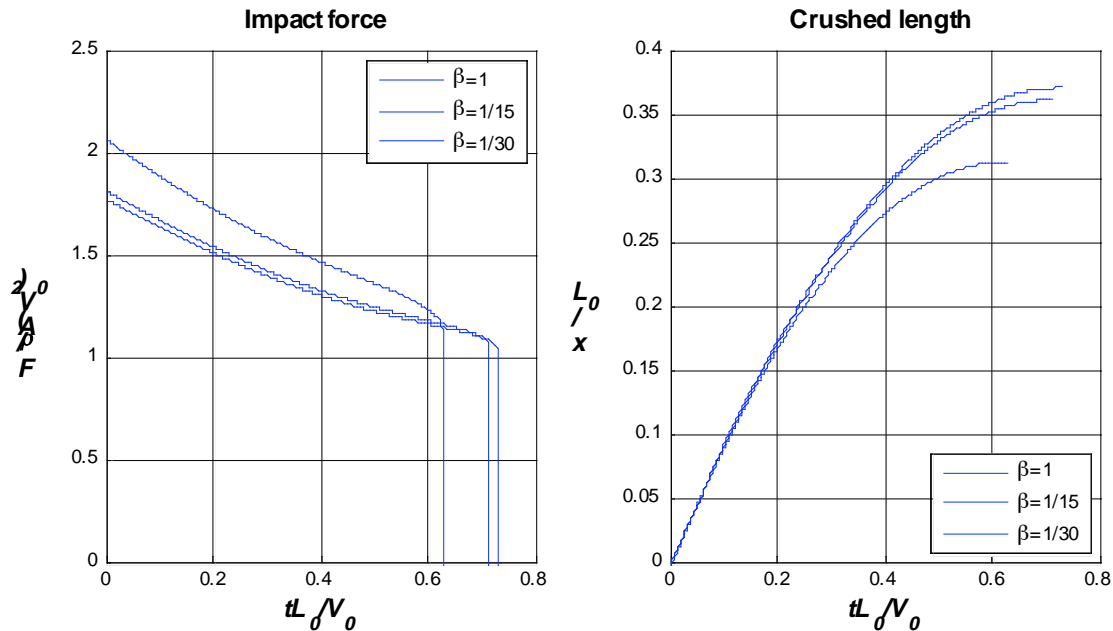


Figure 2. Dimensionless impact forces and missile crushing during impact.

It is seen that the initial value for the impact force for the smallest scale is approximately 15 % higher than for the larger scales. Also the final crushed length for the smallest scale is similarly 15 % smaller. In this case the impact problem is modelled only using the partial differential equation set (1) and crushing force (3). If all dimensionless groups (5) were fulfilled, these curves would coincide. Now term π_4 is not equal between the scales indicating that the differences are caused by the effect of strain rate. The above results are calculated using the given equations and using aluminium as the material in all scales. Strain rate dependency varies for different materials so the difference seen in Figure 1 applies only in this case.

5 EXPERIMENTAL TESTING

A flexible experimental platform has been created at VTT for intermediate scale impact tests. In the tests, missile is impacted on a deformable concrete wall or on a rigid-like steel force measurement plate. The test facility has been further developed and improved since the first version was taken in use in 2003. The apparatus consists of two main parts. First, a 13.5 m long pressure accumulator is used to provide the required initial energy for the test. The pressure is released to a 12 m long acceleration tube that contains a piston. The piston is used to accelerate missiles to a final velocity from 100 m/s to 200 m/s. The second part of the test apparatus is the target. A rigid-like steel plate used to measure impact forces or a deformable

reinforced concrete wall can be used as a target in the tests. Missile shape can be almost freely adjusted but its dimensions should be in the range of 1 meter and the mass of the missile can be up to 100 kg in some cases. Typical missile mass is around 40 kg. A schematic of the testing apparatus is shown in Figure 3 and the two target types are shown in Figure 4. Examples of two different missile types are shown in Figure 5. Also other target and missile types have been used, see (Lastunen et al. 2007) for more details.

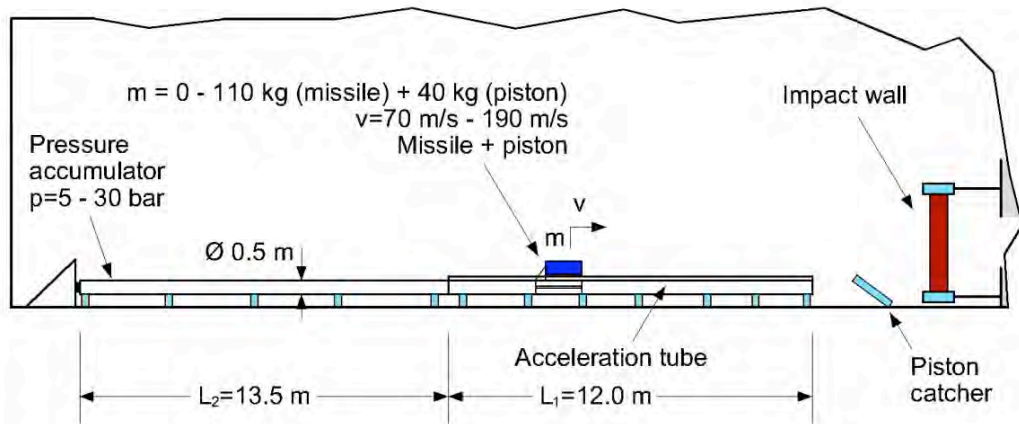


Figure 3. A schematic of the testing apparatus.



Figure 4. Rigid-like steel plate for measuring impact forces (left) and deformable concrete wall (right).



Figure 5. An aluminium pipe missile (left) and a non-axisymmetric missile with wings (right).

This paper concentrates on the non-axisymmetric missile shown on the right hand side of Figure 5. Geometry for this missile is shown in more detail in Figure 6.

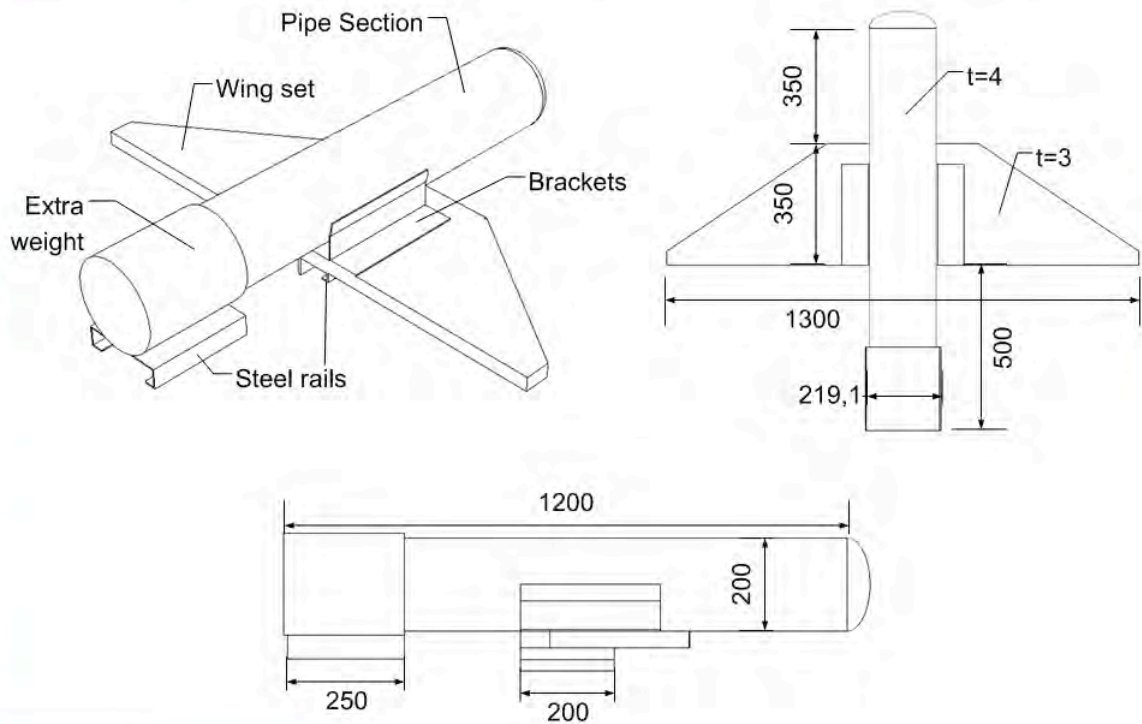


Figure 6. Non-axisymmetric missile structure. Dimensions in millimeters.

In some of the tests in the non-axisymmetric test series small rigid masses were added above the wings and water was included in the wing. The aim of the whole test series was to study 1) change in impact behavior and loads caused by the wing compared to cylindrical missile impact, 2) the effect of the hard masses in the impact loads and 3) the spreading and loads caused by water erupting from the wing.

Various data is gathered during testing. The main measurements are the compressive forces caused by missile impact on the steel plates or the strains and displacements from the reinforced concrete wall. Also support forces and deformations from the target structure in both cases are measured. Other measurements include high speed cameras to capture the impact and accelerometers to obtain missile and wall motion.

Test 687 is discussed in the current paper. Its specifications are given in Table 2.

Table 2. Missile and test properties of Test 687.

Pipe diameter (mm)	200
Wing width (mm)	1300
Missile Length (m)	1.2
Pipe wall thickness (mm)	4
Wing wall thickness (mm)	3
Hard steel pipe impactors	$D=101.6$ mm, $M=1.5$ kg (each)
Total mass (kg)	41.0
Impact velocity (m/s)	136

A few frames from the video captured during the impact are shown in Figure 7. The impact forces are presented later combined with the calculated impact forces. It can be seen that the missile hits the target straight and rotates nose up as it decelerates.

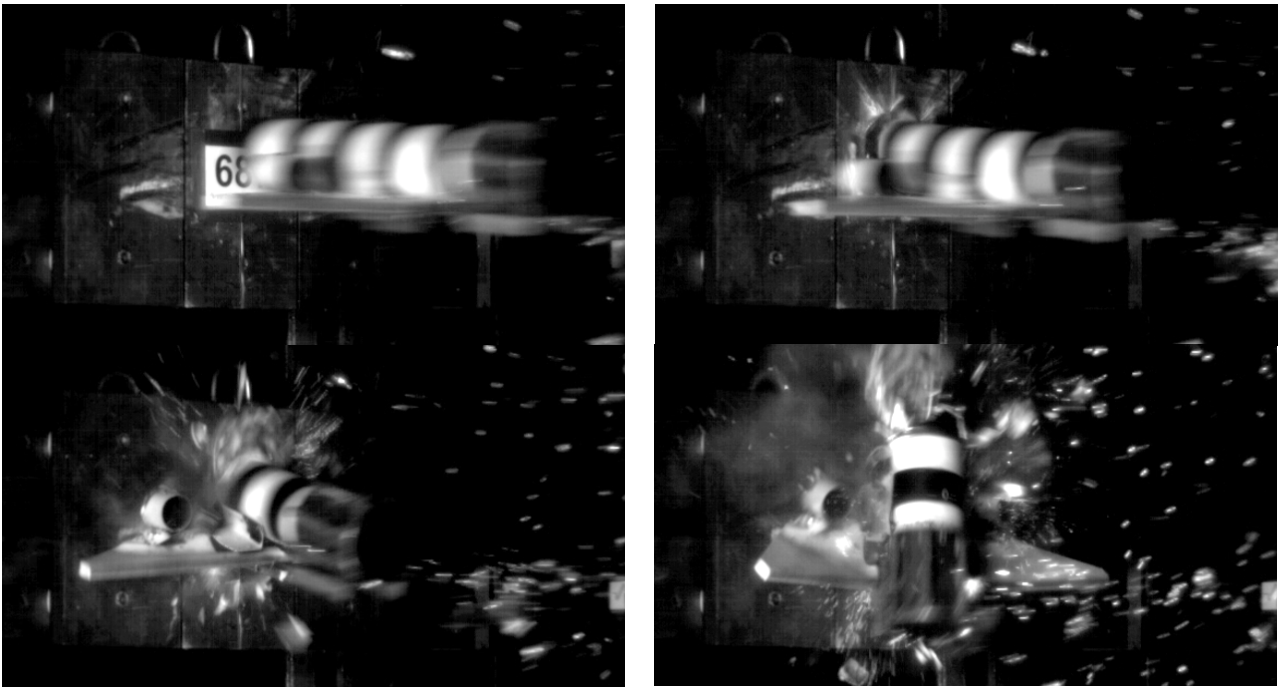


Figure 7. Video frames of missile impact in Test 687.

6 NUMERICAL ANALYSIS

First the impact forces caused by the missile are analysed using Riera's method outlined in Section 2. The crushing force for the fuselage part was calculated using (3) and the crushing force for the wing was determined using a finite element model of the wing.

A more detailed analysis of missile impact is carried out using a finite element model of the missile. The analysis is carried out using Abaqus/Explicit commercial finite element software. Missile structure is modelled using linear shell elements. Plasticity is included using the experimentally measured tensile test data for all the materials. The fuselage, wing and engines are modelled as separate instances that are connected using damaging connectors. The connectors model the actual riveting of the structure. Target is modelled as rigid in the simulation and the dynamic effects of the supporting frame are neglected. Initial velocity matching the measured impact velocity is assigned for the missile. The element mesh of the missile is shown in Figure 8.

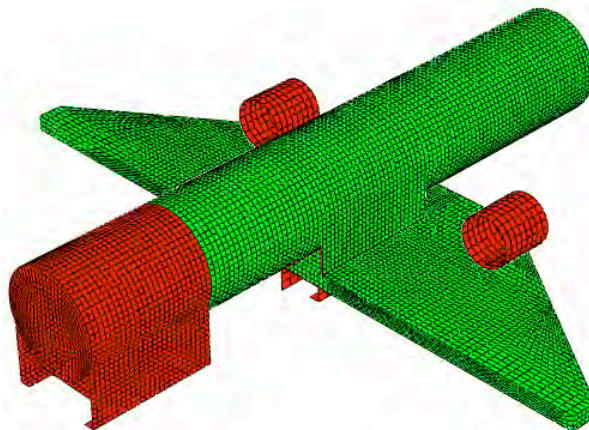


Figure 8. Finite element model of the missile. Steel sections are colored red and aluminium sections are colored green.

Snapshots from the numerical simulation are shown in Figure 9. The times are selected so that they correspond the video frames shown in Figure 7.

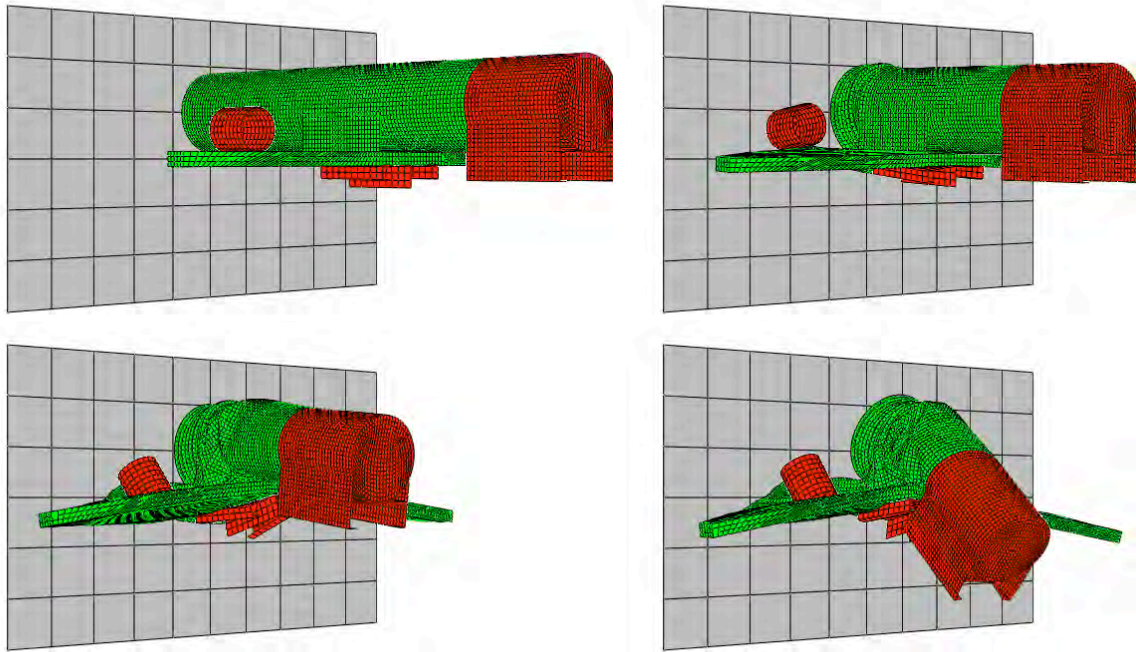


Figure 9. Snapshots from the numerical analysis of missile impact.

The impact forces caused by the missile are now obtained in three ways; Riera's method, numerical finite element simulation and experimental testing. These three force curves are shown in Figure 10. The results are presented in proportion with the results obtained using the Riera's method, i.e. the maximum force given by the Riera's method is scaled to unity.

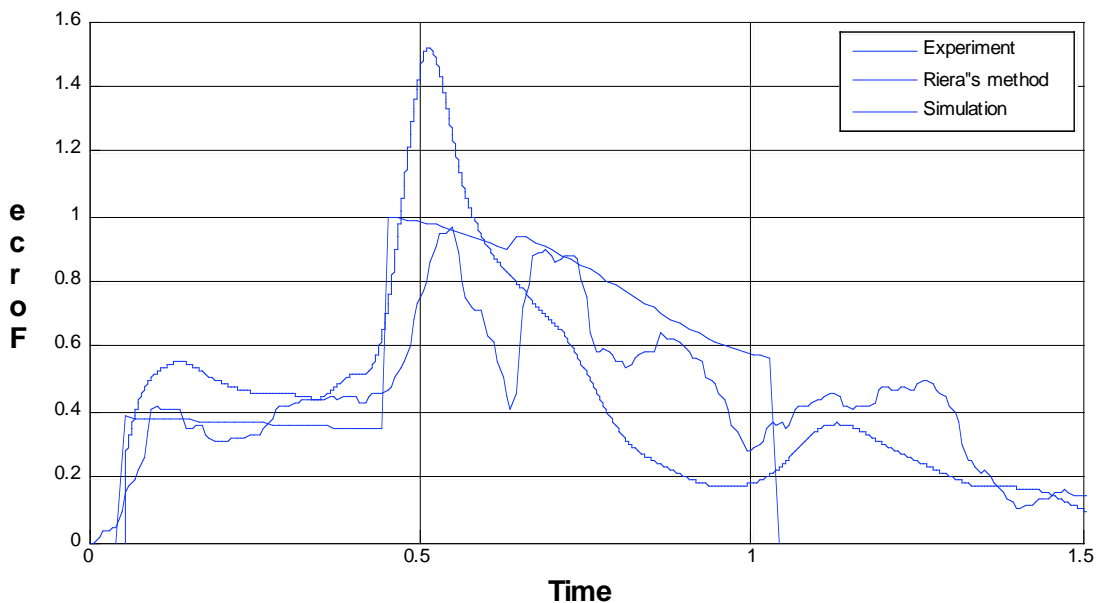


Figure 10. Impact forces caused by the missile calculated using Riera's method, finite element simulation result and experimentally measured data.

From Figure 10 can be seen that the front section and maximum impact forces caused by the wing section correspond well in Riera's method and experimental data. The simulation produces a higher peak that decays fast in the impact loads when the wing impacts the target indicating that the element model is too rigid. Experimentally measured forces and numerical simulation impact forces oscillate more than the impact forces calculated using the Riera's method because the crushing force approximation used. The experimentally measured force curve includes the dynamic effects of the target supporting structure so that the curve cannot be directly interpreted as the contact force between the target and the missile.

7 CONCLUSIONS

Numerical and experimental studies of deformable and hard missile impacts against rigid and deformable targets have been made by VTT Technical Research Centre of Finland. Experimental testing can be carried out using various missiles. Important measurements made in the tests are the impact forces or the target deformations. Impact of a deformable missile with wings was studied in the paper.

The tests are medium scale. Due to the nonlinear effects of in the phenomenon, scaling laws dictate that the results are not directly applicable in other scales. It was found in the current model that smaller scales yield to comparatively higher impact forces but smaller missile deformation. Impact models are verified based on the experimental results. If the models are able to predict impact behaviour in smaller scale, they can be applied to larger scales also, provided that the deformation mechanisms are similar in both scales.

Lastly the impact forces caused by the deformable missile with wings were presented. The forces were calculated using Riera's method and finite element simulation. Also the experimental test result was included. Reasonable match between the impact forces were found. Finite element simulation produced a more rigid impact with higher maximum peak force values. Impact force levels calculated using Riera's method matched the experimental findings.

Presented impact forces were obtained using three separate methods; experimental testing, Riera's method and finite element simulation. All of these have their own challenges. Experimentally measured forces include the dynamic effects of the target supporting structure, Riera's method is strongly dependent how the crushing force is defined and finite element simulations require that the material failure behaviour is modelled accurately.

It can be concluded that for qualitative purposes the two calculation methods provided valuable data. Experimental testing verified the usability of the models. In complex impact scenarios, experimental testing provides data only for the problem in question and its applicability in other cases must be verified using other methods.

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