COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL PREDICTIONS OF THE INTERFACE FORCE DUE TO SOFT MISSILE IMPACT.

Ignácio Iturrioz
Prof. Programa de Posgraduação em Engenharia Mecânica (PROMEC), UFRGS.
email: ignacio@mecânica.ufrgs.br

Jorge Daniel Riera
Prof. Curso de Posgraduação em Engenharia Civil (CPGEC),UFRGS.
e-mail: riera@cpgec.ufrgs.br.

Tomás Wayhs Tech
Graduando Curso de Engenharia Mecânica, UFRGS.
e-mail: tomas.tech@ufrgs.br

Abstract

The study of impact has numerous applications in various engineering fields, such as in the design of reinforced or prestressed concrete barriers against either the accidental or intentional impact of projectiles, or in the evaluation of the crush-worthiness of highway or railway vehicles. In both cases it is necessary to determine the non-linear, large displacements and deformations response of the impacting projectile, as a pre-requisite for the accurate evaluation of the inter-face forces between projectile and target structure.. Due to the non-linear nature of the problem and to the usually complex geometrical properties of both projectile and target structure, theoretical studies are rarely feasible. Thus, recourse must be made to purely numerical evaluations, supplemented if possible by an experimental validation, unless a large body of experimental evidence that confirms the applicability of the computational tools is already available.

This paper presents an assessment of the predicting capability of the computational system LS-DYNA, by comparing results obtained by means of a refined finite element model of an axially symmetrical steel projectile that impinges against a rigid target with experimental and theoretical determinations of the interface force between projectile and target structure for a series of tests conducted in the UK in the early 70's (Alderson et. al, 1977, Bignon & Riera, 1980). In those tests, the target reaction force versus time function, due to a projectile impact at 215m/s, as well as the final deformed configuration of the projectile were determined.

The experimentally determined reaction-time curves are closely reproduced both by the simple uni-dimensional discrete model analysis proposed by Riera (1980) as well as by a three-dimensional finite element shell model implemented in computational system LS-DYNA. Note that the expected value of the reaction as well as the rms value of the fluctuations around the mean are adequately modeled in both cases. The latter are very sensitive to the properties assumed for the model, revealing the chaotic nature of the process, clearly visible in the experimental records.

***Keywords**. Impact load, Finite element methods, projectile crash*

1. Introduction

The prediction of the outcome of impact of projectiles against a target structure may require a coupled analysis, that is, projectile and structure must be jointly modelled and the response obtained by numerical integration, with the initial conditions defined by the impact velocity of the projectile. Such an analysis requires in turn large storage capacity and processing time, and implies as well large model uncertainties. The problem is considerably simplified whenever *uncoupled analyses* are feasible. This is the case when the structure does not completely fail, nor experiences very large local displacements. In the uncoupled approach, the load acting on a rigid target surface, due to the projectile impact, is used as an exterior transient load to assess the behavior of the structure, as proposed by Riera (1980) in connection with aircraft impact against Nuclear Power Plants structures. Note that the uncoupled analysis permits the verification of the interface loads, by comparison of the numerical predictions with other theoretical results or, if available, with experimental evidence. This is extremely important, in view of the difficulties posed by the problem, which involves large deformations and displacements, cracking and/or fragmentation, plastic or other nonlinear features of the material, resulting in very large model uncertainty. It should be recalled that *model uncertainty* refers to the variability in the theoretical predictions due solely to the model employed in the analysis.

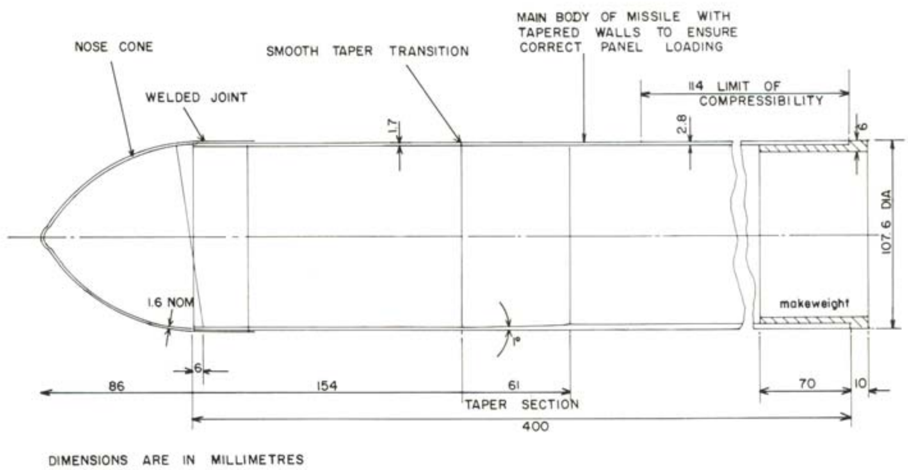
In this paper the predictions of the nonlinear response of steel projectiles that crush at 215m/s against a stiff target furnished by two theoretical models, are compared with experimental results (Alderson *et al*, 1977), to assess the uncertainty implied in both numerical methods, namely:

- Model 1: Simplified unidimensional model, defined by the cross-sectional crushing strength and longitudinal mass distribution (Riera, 1980)
- Model 2: Detailed Finite elements model, allowing for geometrical and material nonlinearities and resorting to explicit time integration, as implemented in Computer Code LS-Dyna.

The characteristics of the experimental projectiles, testing and results are presented in Section 2. A brief description of the theoretical basis of Model 1, as well as all relevant data for the corresponding model of the projectile are given in Section 3. Similar information in connection with Model 2 is summarized in Section 4. Finally, Sections 5 and 6 contain a critical comparison of experimental and numerical results, as well as an evaluation of model uncertainty for impact of *soft* projectiles against stiff targets and the conclusions, respectively.

2. Experimental program

The dimensions and main characteristics of the projectile tested in the British experimental program (Alderson *et al*, 1977) are shown in Fig 1. The projectile constitutes a reduced scale model of the 6 m long projectile tested in Meppen (Germany) and hence had the advantage of permitting the performance of a larger number of tests, thus providing data on the dispersion of relevant response variables. The material used in the fabrication of the projectile was an aluminium alloy (according to British Standards: HT30 to TF conditions), with a tensile strength of 213-222 MN/m^2, a 0.2% proof stress of 31-148 MN/m2, and elongation of 9%. The total nominal mass of the projectile is 1.6Kg.



Dimensions of UK AEC experimental missile.

Figure 1: Dimensions of experimental missile (Alderson *et.al*. 1977)

Two type of tests were performed: (a) a static test aimed at determining the crushing strength of the projectile cylinder, the results of which are shown in Fig. 6 in terms of force vs. axial displacement for four specimens and (b) impact tests, (projectile impact at 215m/s against a rigid target). The projectiles were launched by a gas cannon, and the reaction at a target plate recorded for further processing. The resulting reaction-time curves for the four tested specimens are shown in Fig. 9.

3. Simplified rigid-plastic unidimensional model (Model 1).

In order to determine the reaction $F_{x(t)}$ due to impact of a *soft unidimensional* projectile, such as an aircraft fuselage, aircraft engine, turbine blade or steel pipe, against a *rigid* target structure, a simplified approach based on the model schematically shown in Fig. 2, was proposed by Riera (1968) and extensively used afterwards (Riera, 1980):

$$F_{x(t)} = P_{c\,(x(t))} + \mu_{(x(t)]}\, V^{2}_{(t)} \;; \qquad (1)$$

in which μ denotes the mass of the projectile per unit length , $x(t)$ the distance from the nose of the projectile, $V(t)$ the velocity of the rigid portion of the projectile and the P_c the force needed to crush or buckle the projectile walls. Simple procedures to estimate P_c in engineering problems are discussed by Riera(1980). For the circular cylinder under consideration, one such approach is Rankine´s interaction equation for the elastic buckling load P_e and the plastic yield strength P_y :

$$(1/P_c)=(1/P_e)+(1/P_y) \qquad (2)$$

in wich the elastic buckling load Pe is given by

$$P_e=2\pi h^2E/sqrt(3(1-\nu^2)) \qquad (3)$$

while the plastic yield load is:

$$P_y = 2\pi R\, h\, f_y \qquad (4)$$

where h and R denote the thickness and mean radius of the cylinder, respectively. E and ν represent Young's modulus and Poisson's ratio of the material and f_y its yield stress.

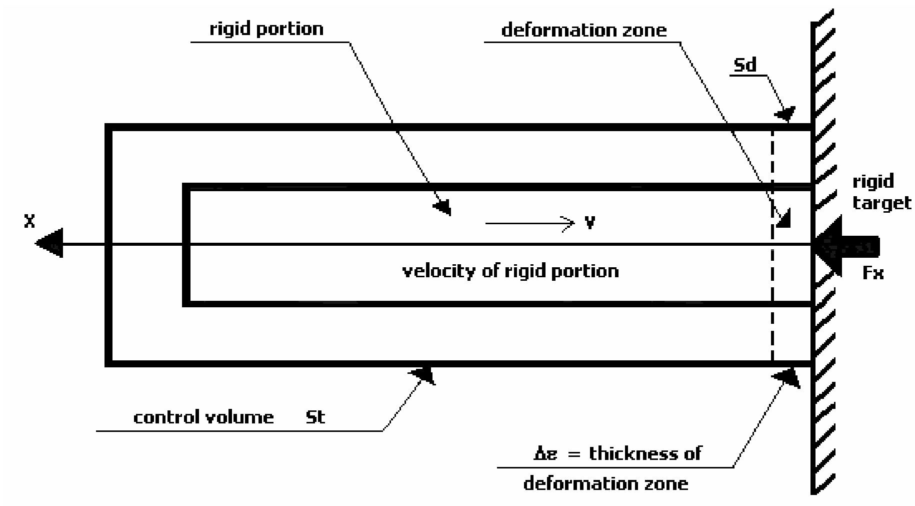


Figure 2: Model of impinging soft missile

The determination of the reaction vs. time curve requires the explicit numerical integration of eq. 1 in the time domain. For such purpose, the projectile was modeled by 62 discrete masses, as shown in Fig. 3. The masses are linked by rigid-perfectly plastic one-dimensional elements.

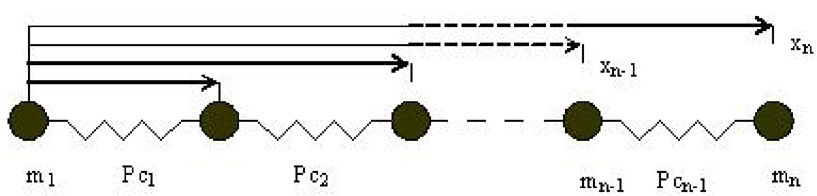


Figure 3: Discrete Model of projectile (Model 1)

4. Refined Finite Element Model (FEM) (Model 2)

The experimental projectile was modeled using thin shell finite elements implemented in the explicit computer code LS-DYNA. The model had 18500 degrees of freedom. The material was characterized by a bilinear elastoplastic constitutive law with softening, with material parameters indicated in Table 1, as illustrated by Fig.4. When an element reaches an ε_r strain, it disappears to facilitate the views in charts 7 and 10. Fig. 5 presents an isometric view of the finite element model, in which the different colors indicate the various thicknesses of the projectile walls

Table 1 Material parameters (model 2)

Propriedade	Valor
Young´s Modulus (E)	0.72E12N/m^2
Tangent Modulus (E_{tan})	8.24E8 N/m^2
Ultimate Stress (σ_r)	220E6 N/m^2
Yield Stress (σ_y)	148 E6 N/m^2
Poisson´s Coefficient (ν)	0.34
ε_y	0.2%
ε_f	9%
ε_r	65%

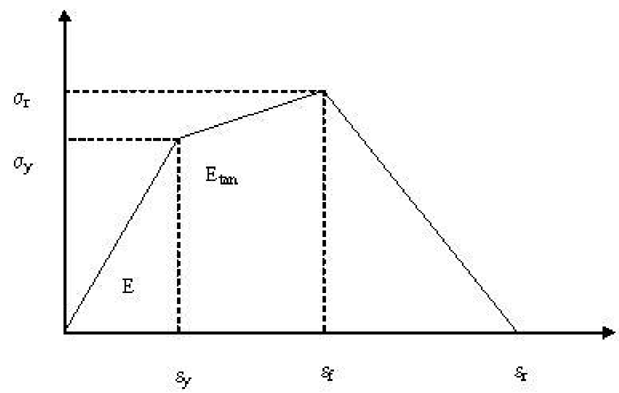


Figure 4: Constitutive law of the material (Model 2).

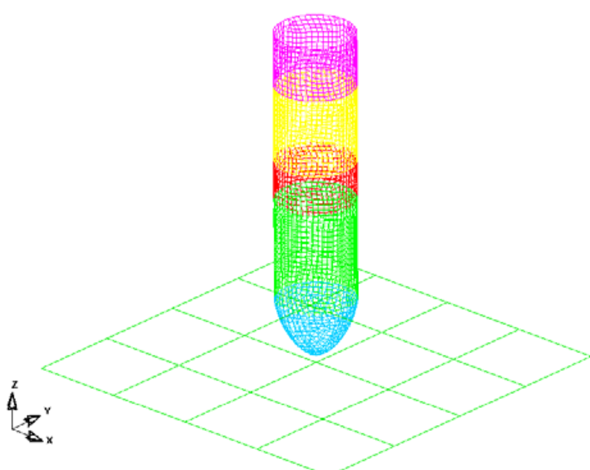


Figure 5: Isometric view of the finite element model (Model 2).

4. Comparison of numerical and experimental results.

In the following, numerical results obtained by means of Models 1 and 2 are evaluated by comparing the numerical and experimental evidence for the reaction vs. time function, and other results, such as length of the crushed region of the projectile and its final configuration.

4.1.Static crushing test.

To evaluate the reaction-time curve using Model 1, only the *mean value* of the crushing load is needed, as a function of position *x*, i.e. distance from the nose of the projectile. For Model 2, a comparison between the experimentally determined crushing load vs. displacement with the numerical predictions seems relevant, to assert its relative influence in relation to the momentum of the projectile mass. Thus, Fig. 6 presents a summary of both experimental and numerical results, as follows: (a) the measured load for four models tested by Alderson *et al* (1977), , (b) the mean curve adopted in Model 1 and (c) the crushing load obtained in a quasi-static simulation with Model 2, in which the load was slowly applied to avoid dynamic effects.

It may be seen that all curves, except (c), presents spikes and valleys, which are due to the buckles characteristic of the buckling modes of axially compressed cylinders do not occur at the same times nor with the same amplitudes. Fig. 7 shows two deformed configurations computed with LS-DYNA

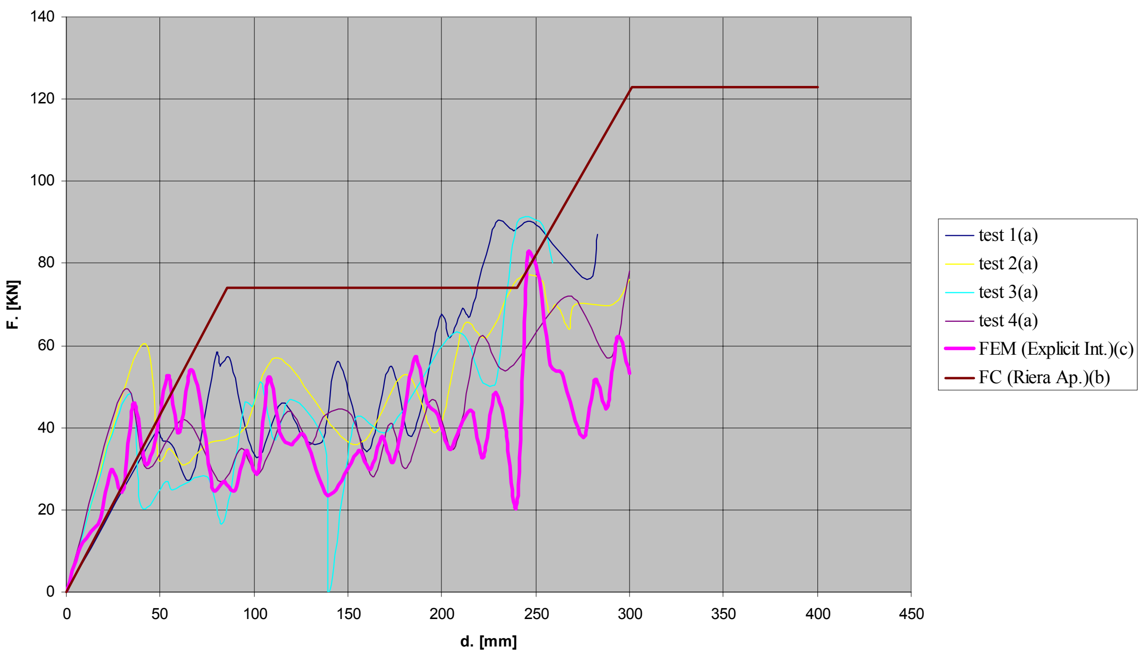
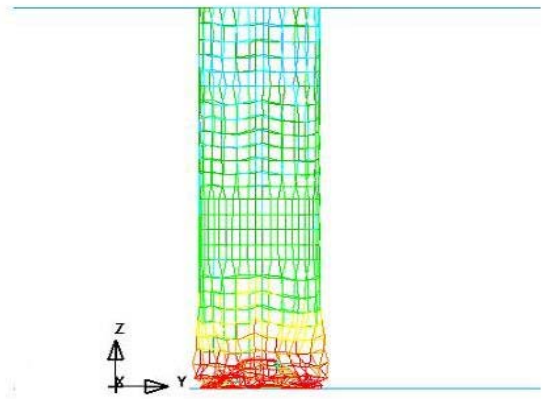
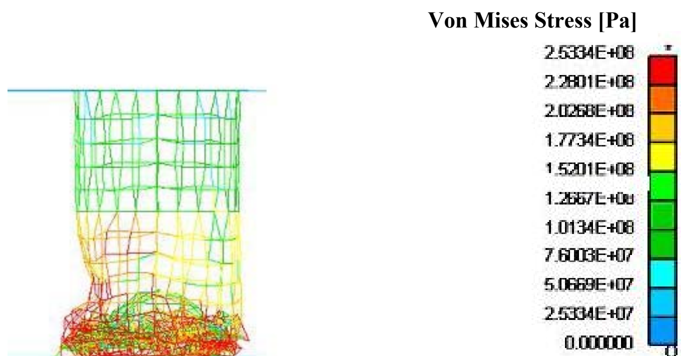


Figure 6: Numerical predictions and experimental results for static crushing load.



(a)



(b)

Figura 7: Deformed configurations and Von Mises stresses for Model 2 in quasi-static analysis.
a) configuration at shortening 288mm, b) Configuration at shortening 410mm.

4.1. Impact load

The experimental reaction-time functions measured by Alderson *et al* (1977) in four tested projectiles impacting against a very stiff target at 215m/s, are shown in Fig. 8. Fig. 9 presents a comparison of the mean experimental curve with the predictions of Models 1 and 2. It is important to note that the predictions of Model 1 represent a mean value of the reaction and should be compared with the *true mean* experimental curve, i.e. with the average of a large number of tests. This mean should likely be a much smoother curve than the five tests mean presented in Fig. 9. On the other hand, the predictions of Model 2 represent the results of just *one numerical simulation*, even if mean values for materials and geometrical properties were used, and therefore they should be compared with the results of the individual tests given in Fig. 8. Fig. 10 shows two deformed configurations of the projectile, for Model 2, in which elements that suffered a strain larger than ε_r were removed from the graph to facilitate visualization. Finally Fig. 11 presents the evolution with time of the residual velocity of the projectile, according to Models 1 and 2. It may be seen that the agreement of both sets of numerical results is excellent

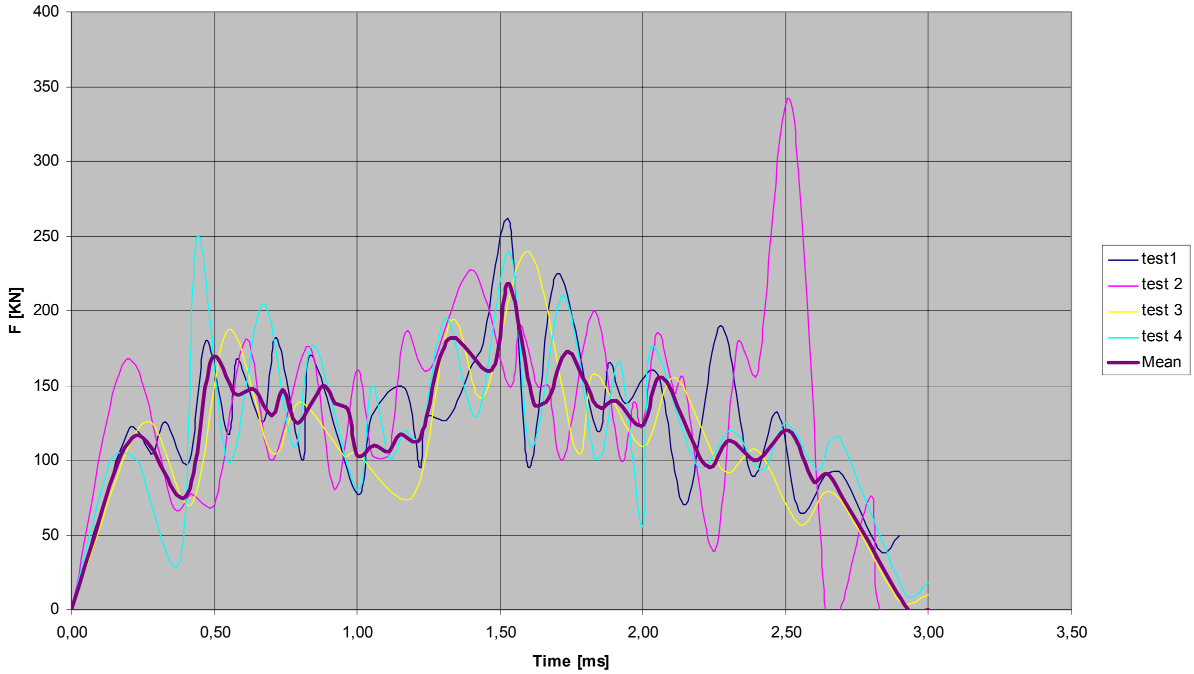


Figure 8: Recorded reactions at missile-target interface for tested projectiles

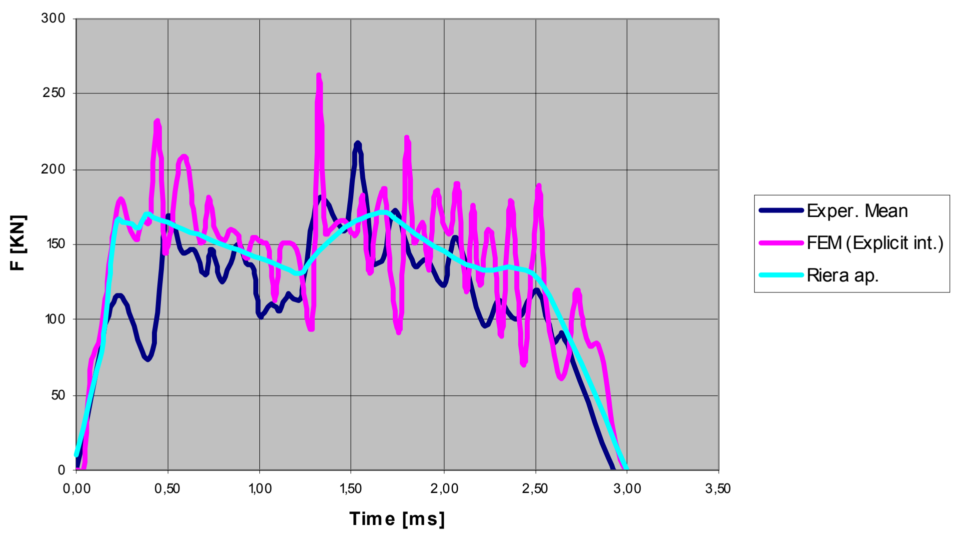
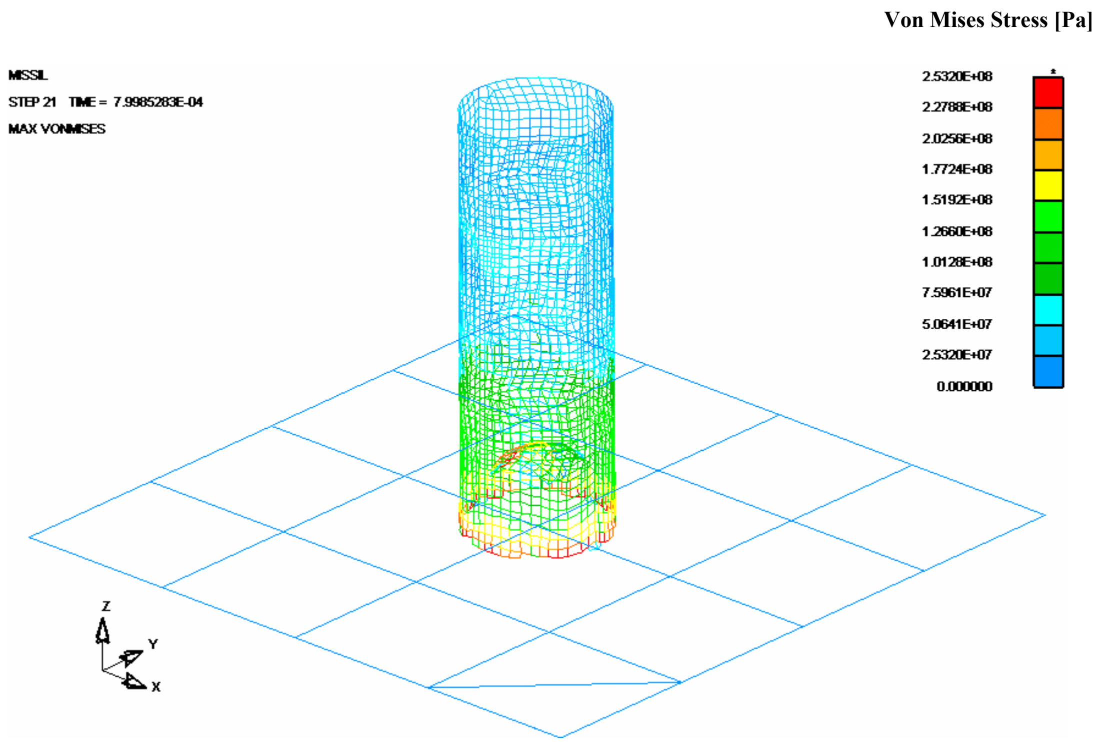
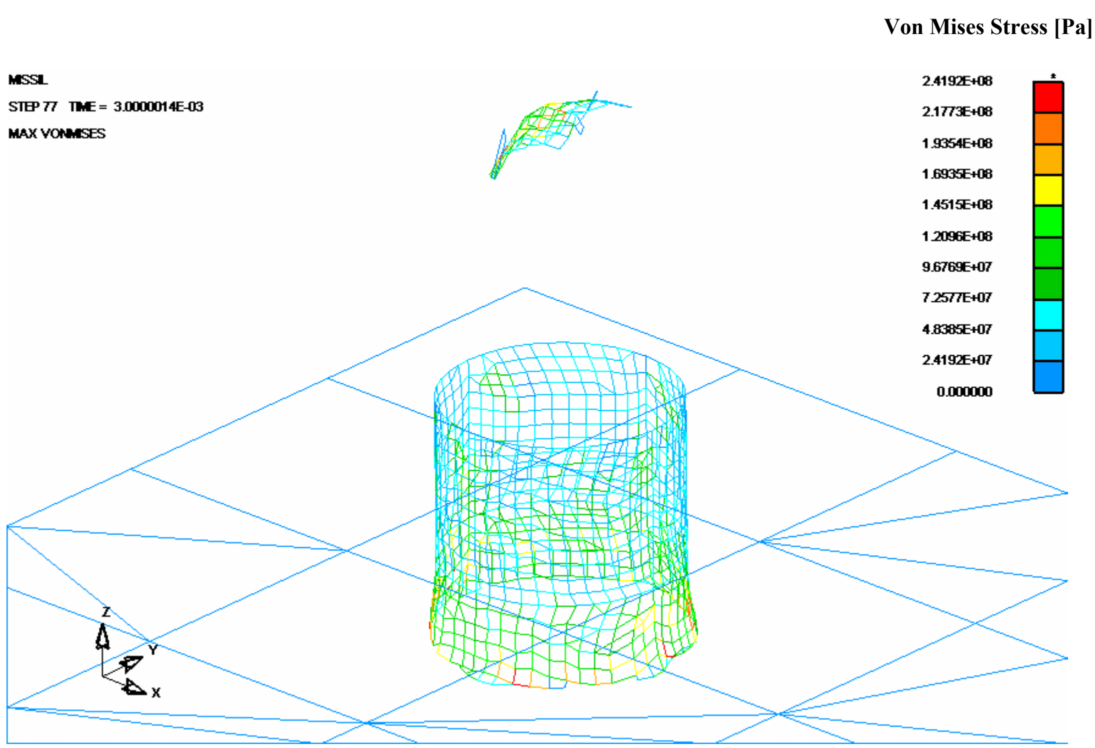


Figure 9: Comparison between experimental and numerical results for the reaction vs. time function at the projectile-target interface.



(a)



(b)

Figure 10: Deformed configurations and Von Mises stresses (Model 2) in impact at 215m/s, (a) time: 0.8ms, (b) time :3ms

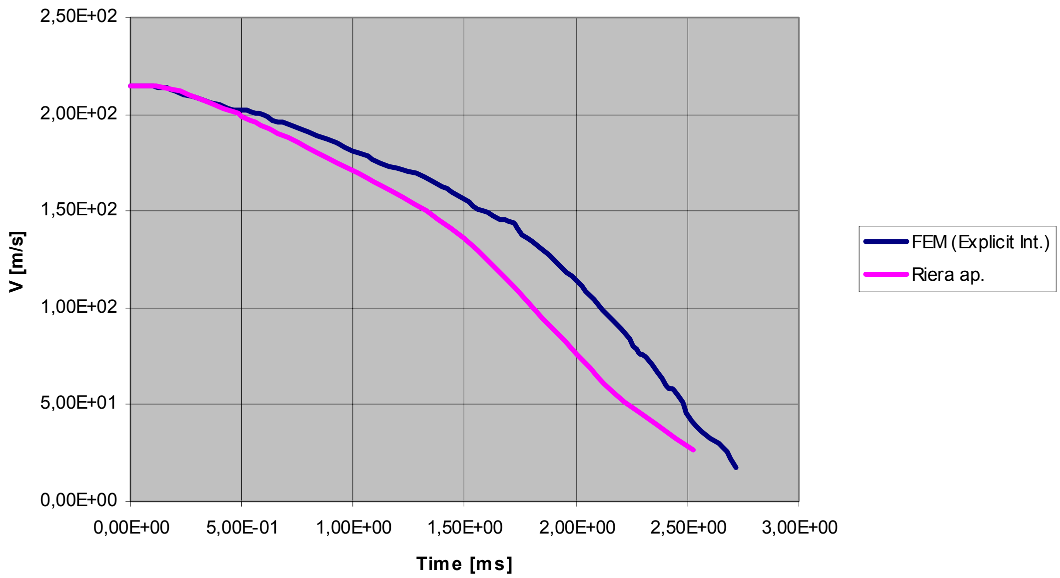


Figure 11: Residual velocity vs time for Models 1 and 2.

6.Conclusions

The prediction of structural response for impact loading constitutes a difficult problem, involving physical and geometrical nonlinearities.This is particularly true in connection with the analysis of soft projectiles, which deform significantly during impact. This situation is encountered in the verification of protective structures under aircraft impact, vehicle impact, turbine blades, and numerous other applications that may be adequately handled by means of an uncoupled analysis. In the paper, the performance of models of widely different level of detailing representative of the projectile is compared with experimental evidence. The results serve as validation of the detailed finite element model, which may now be used in more complex situations, for example, oblique impact against a rough surface. In addition, they furnish valuable information on model uncertainty, that is, on the *errors* introduced by the method of analysis, including the model itself. It is herein stressed that very complex, detailed models should be very carefully examined by comparing its predictions with simple, robust methods of analysis, or experimental data, when available.

7. Acknowledgements
The authors wish to acknowledge the partial contribution of CNPq, and CAPES.

8. References

-Alderson, M.A.H.G.; Davis, I.U.; Bartley, R. & O´Brien, T. P. (1977): SMiRT-4 Transactions, San Francisco, USA, Vol. J, Paper J7/7.
-Bignon, P.G. & Riera, J.D. (1980): "Verification of Methods of Analysis for soft missile impact problems", *Nuclear Engineering and Design, North-Holland,* 60, 311-326.
-Riera J. D. (1968): “On the stress analysis of structures subjected to aircraft impact forces”, Nuclear Eng. &Design, North- Holland, 8, (1968),pp.415-426.
- Riera J. D. (1980): “ A Critical Reapraisal of Nuclear Power Plant Safety Against Accidental Aircraft Impact” *Nuclear Engineering and Design*, North-Holland, 57 , 193-206. North Holland.

9. Copyright Notice