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TURBINE MISSILE IMPACT ASSESSMENT - COMPARISON OF RESULTS FROM EMPIRICAL FORMULAE & FINITE ELEMENT ANALYSIS

Ivaylo Klecherov[1], Dr. Manya Deyanova[2], Anton Andonov[3]

[1] Structural Engineer, Mott Macdonald Ltd, Bulgaria
[2] Structural Engineer, Mott Macdonald Ltd, Bulgaria
[3] Principal Engineer, Mott Macdonald Ltd, Bulgaria

ABSTRACT

This paper presents a comparison of the results from empirical mathematical methods (ETC-C, R3 Impact Assessment Procedure and Forrestal penetration model) with nonlinear finite element analysis used to study the impact of a large scale turbine disc into a reinforced concrete wall. The complex model of the turbine disc is transformed into an equivalent cylindrical projectile in order to be implemented in the empirical procedures. Results from the empirical methods are compared with the results from a missile-target interaction analysis with the LS-DYNA finite element code including detailed models of the turbine disc and the target structure.
The target is modelled with nonlinear material rules for the concrete and the reinforcement, including material erosion. In addition, as a verification, simple impact scenarios are studied with both empirical methods and finite element analysis. The results obtained show that when the turbine projectile is significantly different from the equivalent cylindrical projectiles on which the empirical methods are based, the more suitable method for assessment is the missile-target interaction analysis using detailed finite element models of both the turbine missile and the target structure.

INTRODUCTION

Turbine missile impact is one of the major anthropogenic loads on safety critical nuclear structures. It is a high consequence event with low probability of occurrence, typically in the 10^{-7} range. Mass of the turbine missile in the range of 5-15 tonnes. Because of its low probability of occurrence the turbine missile impact is usually analysed using best estimate approaches in line with the concepts for beyond design events / design extended conditions.
There are several methods available to analyse the perforation resistance of a RC structures impacted by hard missiles. They can be grouped in two main groups: methods based on empirical formulae and methods based on finite element analysis. All empirical methods are based on missiles with cylindrical shape. Since the geometry of the turbine missile deviates significantly from a cylindrical missile, difference in the predicted damage is expected.
This paper is based on parametric study of a hypothetical turbine missile impact on a RC structure focusing on the assessment of the difference in the results obtained with empirical formulae and finite element analysis.

PROBLEM DESCRIPTION

The study presented herein is an excerption from a wider study on a multi-compound safety critical nuclear facility. The original task was to assess how many walls will be perforated, i.e. how many safety systems will be lost under a particular turbine-missile impact scenario. The turbine missile impact scenarios are defined as turbine disks with different size/mass, different geometry (1/3 or 1/4 of a disk), different impact velocities and impact trajectories. An example for one of the impact scenarios (with sub-scenarios about the potential orientation of the turbine disk at the time of impact) is given in Figure 1.

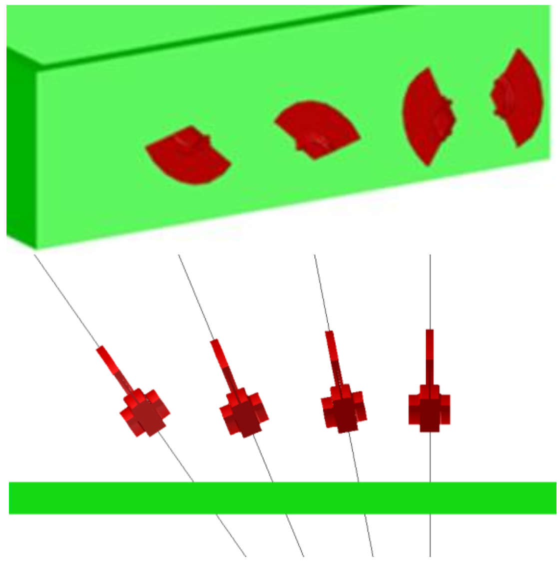

Figure 1. Schematic of turbine missile potential orientation against the concrete walls.

Turbine Missile

For the purposes of this paper, a generic turbine disk blade is used. It is assumed that the turbine blade is a quarter of a disk – sectoral angle of 90°. The diameter is assumed 3m, mass is 7600kg. The geometry of the turbine disk blade is presented in Figure 2.
The material is assumed high-strength steel with mass density of 7850 kg/m^3.

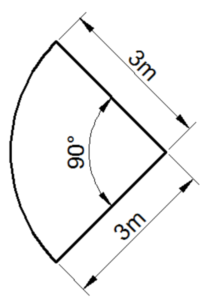

Figure 2. Geometry of the turbine disk blade.

Target Building

For the purposes of this paper, the target building is simplified and represented as a part of the external RC wall. The wall thickness is assumed to be 1 metre with concrete compressive strength f_{cm} assumed to be 40MPa, The concrete density ρ_c is 2500 kg/m3 and the maximum aggregate size is 20mm of diameter.

The flexural reinforcement is two-way grid on each face of 40mm diameter bars at 200mm centres. The shear reinforcement connects the intersection points of the horizontal and vertical rebars on the front face with the intersection points of the rebars on the rear face, i.e. 200mm spacing in each direction. Both, bending and shear reinforcement are assumed of the same steel grade, B500C with $f_y = f_{ys}$ = 500MPa and total elongation at maximum force 8.5%.

ANALYSIS METHODS

In the current paper there are two methods of analysis used – the empirical mathematical method for simplified numerical calculations, and the full scale finite element method using the direct missile-target interaction analysis in LS-DYNA.

EMPIRICAL FORMULAE

There are three empirical methods used in the current paper. All three of them define procedures for calculation of perforations of reinforced concrete targets by non-deformable missiles (hard impact). A description of each method is given further in the text.

ETC-C Penetration Formula

The first empirical method used is based on the penetration formula described in ETC-C (2012). The penetration formula in Equation 1 contains the mass M, diameter D and velocity V_p of the missile, and concrete parameters such as f_{ck} and ρ as well as the thickness of the wall H.

$$\frac{\rho_c \cdot V_p^2}{f_{ck}} = 1.89 \cdot \left(\frac{\rho_c \cdot H^2 \cdot D}{M}\right)^{\frac{4}{3}} \tag{1}$$

The minimum velocity of a missile, needed to perforate the concrete target, is obtained from Equation 1. The value obtained is used for the calculation of the residual velocity of the missile. The residual velocity after perforation is assumed to be the difference between the initial velocity before impact and the velocity needed for perforation (Equation 2).

$$V_r = V_i - V_p \tag{2}$$

The method defined is applicable to the validity ranges of some of the parameters used (Equations (3), (4) and (5)).

$$20 \text{ m/s} < V < 350 \text{ m/s} \tag{3}$$

$$1250 \text{ kg} < M < 12500 \text{ kg} \tag{4}$$

$$0.5 \text{ m} < D < 1.5 \text{ m} \tag{5}$$

The equations of the validity ranges are obtained for the assumed target wall thickness of 1 metre.

R3 Impact Assessment Procedure

The second method is based on the perforation formula of R3 Impact Assessment Procedure (2009). The perforation behaviour is described in terms of critical, i.e. minimum impact energy E_p, required to just achieve perforation, which implies that the residual velocity of the missile after target perforation is zero.
Perforation by hard missiles is defined in two main categories. First, when $H/D < 5$, the target is considered thin and the damage is sensitive to the amount of reinforcement. If $0.5<H/D<1.0$, Equation (6) must be used. Equation (7) must be used when $1.0<H/D<5.0$. When $H/D \geq 5$ the target is considered thick and the damage is not sensitive to the amount of reinforcement, Equation (8) must be used.

$$\frac{E_p}{\eta \cdot \sigma_t \cdot D^3} = -0.00506 \cdot \left(\frac{H}{D}\right) + 0.01506 \cdot \left(\frac{H}{D}\right)^2 \tag{6}$$

$$\frac{E_p}{\eta \cdot \sigma_t \cdot D^3} = -0.01 \cdot \left(\frac{H}{D}\right) + 0.02 \cdot \left(\frac{H}{D}\right)^3 \tag{7}$$

$$\frac{E_p}{\sigma_t \cdot D^3} = \frac{\pi}{4} \cdot \left(\frac{H}{D} - 3.0\right) \tag{8}$$

The perforation formulae (6), (7) and (8) are given as equations containing the critical impact energy E_p for target perforation and the dynamic resistant pressure σ_t as a function of f_{cm} and V_i. The dimensionless parameter η takes into account the reinforcement diameter and spacing each way, on each face. The energy calculated for the perforation is then used for obtaining the residual energy of the missile (Equation (9)).

$$E_r = E_i - E_p \tag{9}$$

Since the missile's mass is assumed constant, the residual velocity could be readily derived (Equation (10)).

$$V_r = \sqrt{\frac{2 \cdot E_r}{M}} \tag{10}$$

The method defined applies for the validity ranges of some of the parameter used (Equations (11), (12) and (13)).

$$0 \text{ m/s} < V < 350 \text{ m/s} \tag{11}$$

$$1 \text{ kg} < M < 2622 \text{ kg} \tag{12}$$

$$0.022 \text{ m} < D < 0.6 \text{ m} \tag{13}$$

Penetration Model of Forrestal

A further study to the methods ETC-C and R3 has been performed using the penetration model of Forrestal as described by Forrestal et al. (1994). Further research by Tuomala et al. (2010) suggested an extension of the penetration model to a perforation model, including the capacity of the concrete and the reinforcement. If the contact force acting on the target is larger than the capacity of concrete and reinforcement, target perforation occurs.

The penetration model describes two main phases. First, at surface crater formation, or scabbing, the contact force F (Equation (14)) at the nose of the missile is:

$$F = c \cdot u \qquad \text{for } 0 < u < kD \tag{14}$$

For a sufficiently high speed, tunnelling occurs as a second phase. The contact force F (Equation (15)) is then:

$$F = \frac{\pi D^2}{4}\left(S \cdot f_{cm} + N \cdot \rho_c \cdot V^2\right) \qquad \text{for } u > kD \tag{15}$$

In the equations above u is the penetration depth, k is a factor, N is the nose shape factor, S is the concrete confinement factor and the constant c is derived from the conditions of continuity of force, velocity and displacement between the crater and tunnelling phases.
Thereafter, the equations of motion suggested by Forrestal et al. (1994) are solved numerically.
Assuming that a conical plug is formed in front of the missile nose, the resistance of the shear surface due to concrete is as in Equation (16)):

$$F_{sc} = \tau_c h_p \pi (D + h_p \tan \alpha) \tag{16}$$

$h_p = h - u$ is the remaining target thickness in front of the projectile, τ_c is the shear strength of concrete and α is the angle between the meridian direction of the conical surface of the shear plug and the missile axial direction.
The reinforcement is taken into account and the resistance of the flexural reinforcement (Equation (17)) is calculated as follows:

$$F_{sb} = \pi (D + h_p \tan \alpha) A_s f_y \sin \alpha \tag{17}$$

where f_y is the yielding strength of the reinforcing rebars and A_s is the area of bending reinforcement per unit width. The resistance of the shear reinforcement (Equation (18)) is:

$$F_{ss} = \pi h_p (D + h_p \tan \alpha) A_{ss} f_{ys} \tan \alpha \tag{18}$$

where f_{ys} is the yielding strength of shear reinforcing bars and A_{ss} is the area of shear reinforcement per unit area.
The total resisting force (Equation (19)) is the sum of Equations (16), (17) and (18):

$$F_s = F_{sc} + F_{sb} + F_{ss} \tag{19}$$

If the contact force F is larger than the resisting force F_s, perforation occurs. Residual velocity V_r is then directly obtained from the current time step of the equations of motion.

Definition of equivalent cylinder

Because all of the methods described above are based on a missile with cylindrical shape, the turbine missile must be converted in an equivalent cylinder. The equivalent cylinder is defined by its length, which is assumed equal to the turbine radius (Figure 3). The radius of the equivalent cylinder is then calculated using the mass of the missile and the mass density of steel (Equation (20)).

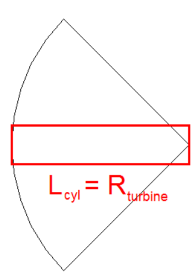

Figure 3. Equivalent cylinder definition.

$$R_{cyl} = \sqrt{\frac{4 \cdot M}{\pi \cdot L_{cyl} \cdot \rho_s}} \tag{20}$$

FINITE ELEMENT ANALYSIS

The finite element model is created with the pre/post processor of LS-DYNA (LSTC, http://www.lstc.com, LSTC, 2014).

Turbine Missile Modelling

The turbine blade missile is modelled in two parts. Firstly, the rigid body is modelled, then the fan of the turbine disk is added. Due to the complex geometry, the fan is simplified and is modelled with a single layer of solid elements.
The turbine blade missile (Figure 4) is modelled with 7040 solid finite elements with single integration point formulation.

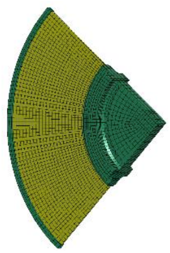

Figure 4 – Finite element model of the turbine disk

The steel material is modelled using MAT024 – Piecewise Linear Plasticity model. It includes the elastoplastic behaviour of the steel as well as strain rate effects based on the Cowper-Symonds (1957) formulation.
Material erosion criterion is assigned as plastic strain to failure – when the plastic strain of a single element reaches a certain value, the element is deleted from the calculation.

Target Building Modelling

The target building is modelled with solid finite elements with single point integration formulation for the concrete. For the reinforcement beam finite elements with Hughes-Liu cross-section integration formulation are used.
The finite element model (Figure 5) consists of a total number of 240000 solid elements and 42000 beam elements.

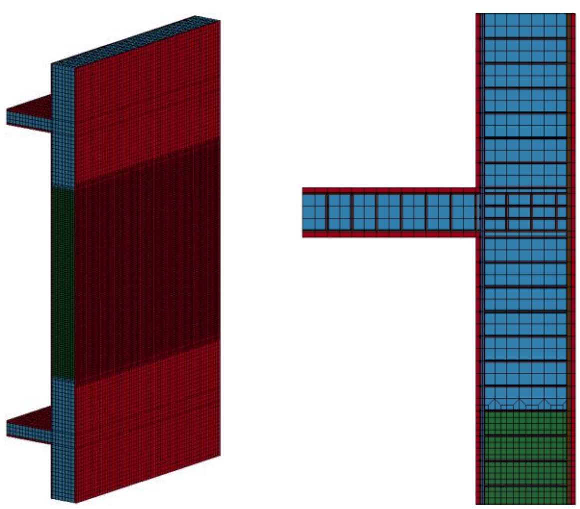

Figure 5 – Finite element model of the concrete target

The concrete is modelled using MAT159 CSCM-Concrete material model.
Material erosion criterion is assigned as strain to failure – when the strain of a single element reaches a certain value, the element is deleted from the calculation.
The general mesh consists of solid elements with side of 0.1m and at the region of the impact, the mesh is refined to 0.05x0.05x0.05m.

The reinforcement is modelled with MAT003 Plastic-Kinematic material model. The input parameters describe the elastoplastic behaviour of the steel, the strain rate effects based on the Cowper-Symonds formulation as well as the erosion criterion. The mesh of the reinforcement is presented in Figure 6.

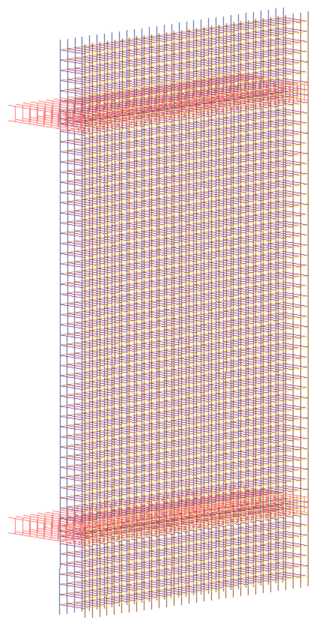

Figure 6 – Finite element model of the reinforcement

Stress-strain curves of the constitutive models of concrete and reinforcement are presented in Figure 7.

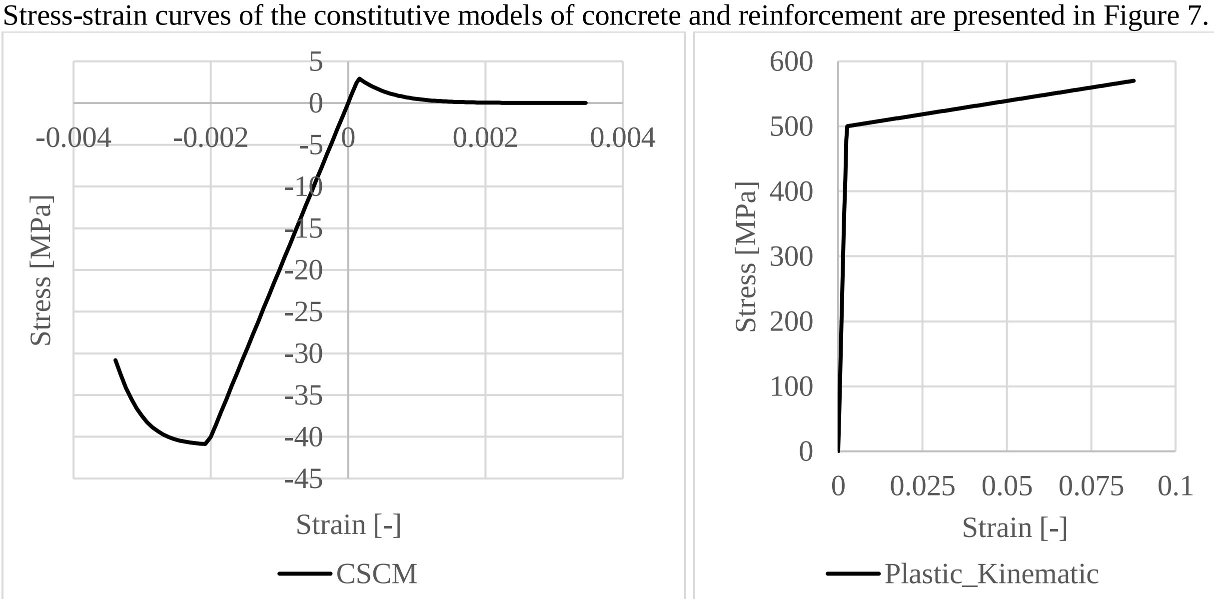

Figure 7 – Stress-Strain relations of concrete and reinforcement

Missile-Target Interaction Analysis

The missile-target interaction analysis is performed using LS-DYNA.
The numerical analyses are calculated using initial velocities of 160, 200, 240 and 280 m/s.
Although, it is expected that after disintegration the turbine disk missile will continue its motion with rotation around its centre of gravity, its rotational velocity is neglected in the analyses performed for this paper.

RESULTS

Results from the turbine disk impact scenario with initial velocity of 280 m/s are given in Figure 8. In all scenarios investigated, the turbine disk perforates the wall, Table 1.

Table 1: Initial and residual velocity comparison

Initial velocity [m/s]	160	200	240	280
Residual velocities [m/s]				
ETC-C	105	145	185	225
R3	137	180	223	264
Forrestal	143	186	228	270
FEA_TD	52	75	120	145

As shown in from Figure 8, the perforation crater has an elliptical form. The residual velocities from the finite element analysis are significantly lower than the residual velocities calculated using the empirical formulae. One of the reasons for this is the different shape of the turbine disk compared to the cylindrical missiles that are used in the analytical assessment.

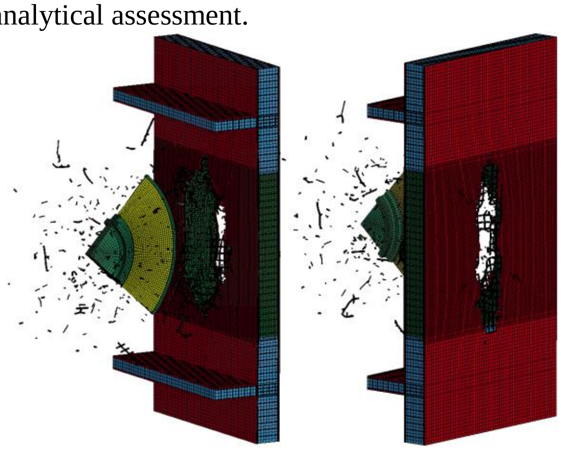

Figure 8 – Turbine missile impact

In order to evaluate the influence of the shape of the missile, additional analyses are performed with a cylindrical missile which has the same mass and geometry as the missile used in the empirical formulae. Results from the equivalent cylinder impact scenario with initial velocity of 280 m/s are given in Figure 9. Comparison of the results from all methods and for all initial velocities is given in Figure 10. Figure 10 shows that the residual velocities from the finite element analyses with a cylindrical missile are still lower than these calculated using the empirical formulae but are much closer compared to the finite element analyses with the turbine disk.

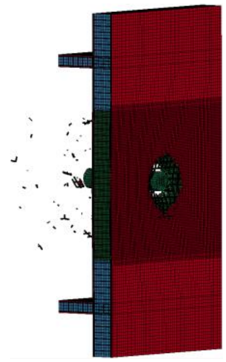

Figure 9 – Hard cylindrical missile impact

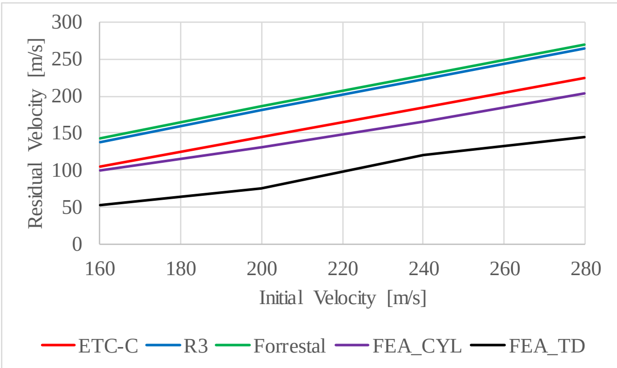

Figure 10 – Comparison of the results of the methods used

CONCLUSION

It can be concluded that for missiles with shapes that significantly differ from the cylindrical missiles used in the development of the empirical formulae, the empirical formulae overestimate the damage potential of the missiles. This can lead to conservative conclusions about the safety of the assessed facility which can adversely affect an element of the licensing process without adding any value to the safety of the asset itself.

NOMENCLATURE

A_s – area of reinforcement per unit width [m^2/m]
A_{ss} – area of reinforcement per unit area [m^2/ m^2]
c – constant [kg/s^2]
D – diameter of cylindrical missile [m]
E_k – initial kinetic energy of missile [J]
E_p – energy for target perforation [J]
E_r – residual energy of missile [J]
f_{ck} – characteristic compressive strength of concrete [Pa]
f_{cm} – mean compressive strength of concrete [Pa]
f_y – yielding strength of bending reinforcement [Pa]
f_{ys} – yielding strength of shear reinforcement [Pa]
F – contact force on the missile’s nose [N]
F_s – total resisting force [N]
F_{sc} – resisting force of concrete [N]

F_{sb} – resisting force of bending reinforcement [N]
F_{ss} – resisting force of shear reinforcement [N]
H – thickness of the concrete target wall [m]
M – mass of missile [kg]
N – nose shape factor [-]
S – concrete confinement factor [-]
u – displacement [m]
V_i – initial velocity of missile [m/s]
V_p – velocity for target perforation [m/s]
V_r – residual velocity of missile [m/s]
η – reinforcement parameter [-]
ρ_c – mass density of concrete [kg/m^3]
ρ_s – mass density of steel [kg/m^3]
σ_t – dynamic resistive pressure [Pa]

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