Hourglass Reduction Measures in Hard Turbine Missile Impact into Concrete Protective Barrier

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Abstract

A turbine disintegration/failure is an event that could generate missiles with different type and speed that could have destructive impact on structures and equipment in power stations. In the current paper a study of impact of a turbine rotor fragment generated during an overspeed event on a reinforced concrete slab is performed. The assessment is conducted with the missile target interaction procedure taking into account the nonlinear material characteristics of both the projectile and the target structure. Special emphasis is given to hourglass energy reduction as a common problem encountered during numerical simulations. Different hourglass control options (IHQ 1,2,4 and 6) and different element formulation (ELFORM1 and ELFORM2) are compared. Another measure to reduce the hourglass energy considered in the study is mesh refinement at the impact area. Summary of the most important results and finding about numerical modelling of missile target interaction analysis conclude the paper.

1 Introduction

Power stations contain pressurised components and rotating machinery (e.g., turbine-generators, diesel generators, pumps, fans, blowers, compressors) that can fail disruptively and cause missiles with destructive kinetic energy for the surrounding structures and equipment. There are historical examples showing that fragments of different sizes and shapes can be ejected in the event of the failure of rotating equipment. Stress concentrations, structural discontinuities, defects in materials and other factors can all affect the failure process and influence the type of fragments formed. A turbine disintegration is a catastrophic event that could generate missiles of different type, weight, rotational velocity and kinetic energy. Turbine disc fragments generated during an overspeed event are taken as the bounding case for these potential missiles. It is the last stage of a turbine moving parts that are most at risk from failure during turbine operation. Low pressure turbine discs are the critical component in any steam/gas turbines and corrosion fatigue has caused most of the damage in that part of the turbine. In terms of the overspeed scenario, the low-pressure cylinder last stage disks/blades are longest and massive and therefore at most risk from tensile failure in an overspeed event. In order to assess the degree of protection and the risk of turbine disintegration missiles challenging safety, a structured approach is to be followed to quantitatively assess the hazard.

In the current study this assessment is done on the basis of the finite element analysis considering contact between the missile and the target. ELFORM1 is usually the solid element of choice when impactive problems are to be solved as it provides efficiency and accuracy. However, this type of element requires hourglass stabilization. Major part of the current investigation is concentrated on the means and methods for hourglass energy reduction and their influence on the final result. Several hourglass control options have been tested, as well as the use of ELFORM2 and mesh refinement within the localized impact area of the target slab. The numerical results are compared to analytical calculation.

2 Finite element models

The computational finite element model is generated using the LS-Dyna PrePost. The generic turbine missile selected for the structural assessment represents 1/3 disk fragment with mass approx. 4000 kg and diameter approx. 3 m. The LS-Dyna material model used for the turbine missile is *MAT_PLASTIC_KINEMATIC (refer to the LS-Dyna Material Manual [1]). The material properties are typical for Nickel-Chromium-Molybdenum steel alloy which is typically used for turbine blades [4]. The assumed properties are given in Table 1. Strain rate strength enhancement is considered via the Cowper-Symonds formula with coefficients typical for steel.

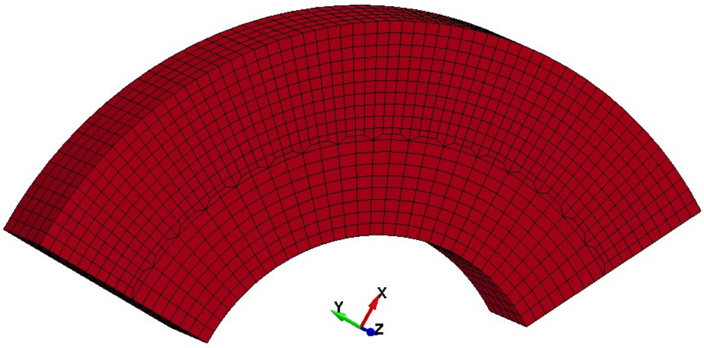

Fig.1: 3D view of the desintegrated disk missile

Modulus of elasticity, [MPa]	Poisson's ratio	Yield strength, [MPa]	Tangential modulus, [MPa]	Erosion strain, [-]
2.01e5	0.3	685	750	0.2

Table 1: Material properties of the turbine missile

The target structure is a reinforced concrete slab. The reinforcement is modelled with beam elements whereas the beam mesh is constarined into the solid mesh via *CONSTRAINED_BEAM_IN_SOLID [1]. The reinforcement properties correspond to reinforcement steel garde B500. Concrete compressive strength is 40 MPa. MAT_PLASTIC_KINEMATIC model is used also for the reinforcement and MAT_CSCM is used for concrete.

3 Analysis results

This part of the paper summarized the results obtained from the finite element analyses. Figure 3 and Figure 4 show the finite element model of the slab with two different mesh sizes - 10cm and 5cm. The mesh is refined in the impact area to reduce modelling and computation effort.

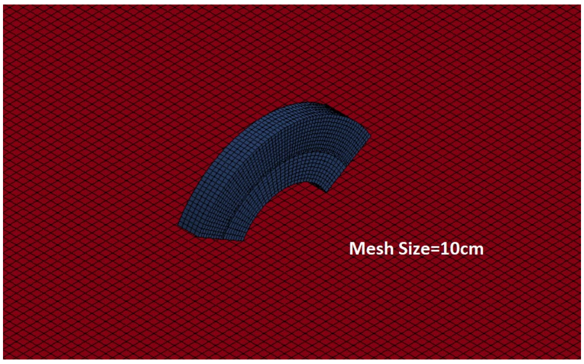

Fig.2: Finite element model of the target building- element size 10cm.

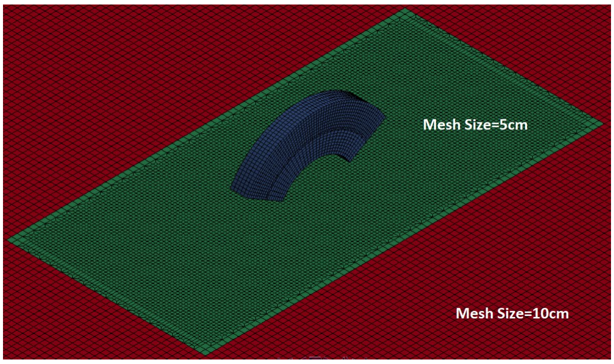

Fig.3: Finite element model of the target building- element size 5cm.

Deformed shape and accumulated damage at the end of the simulation for the 10cm mesh size model is shown an Figure 4, while for the refined mesh in Figure 5. The energy plots of the two analyses can be seen in Figure 6 and Figure 7, respectively.

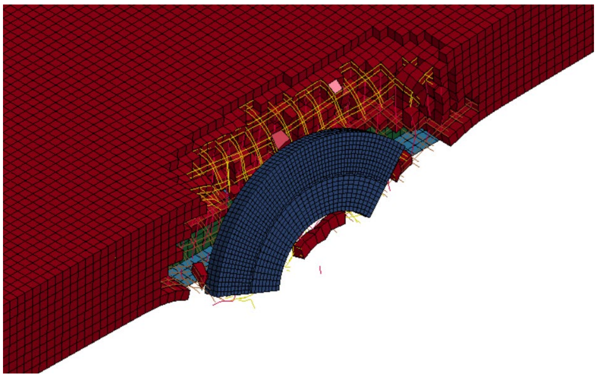

Fig.4: Deformed shape at the end of the analysis- element size 10cm

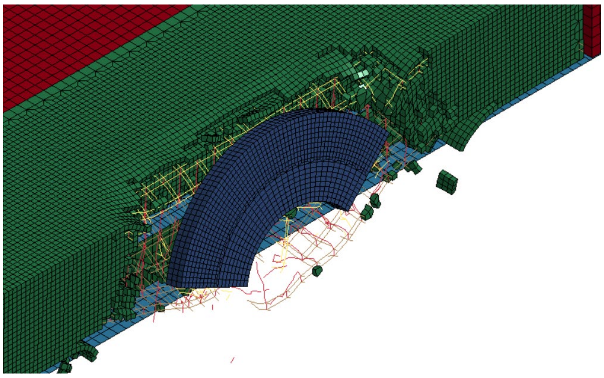

Fig.5: Deformed shape at the end of the analysis- element size 5cm

E.

As it is observed from Figure 6, the hourglass energy of the 10cm element size mesh model is approx. 40% of the internal energy. The reduction of the mesh size to 5cm in the impact area leads to reduction of the hourglass energy to 25.5% of the internal energy as seen in Figure 7. Ideally the hourglass energy should be kept approx. 10% of the internal energy to reduce the effects of the non-physical deformation modes.

As the plots in Figure 6 and Figure 7 demonstarte, for the both cases discussed above, the hourglass energy exceeds this limit. Therefore the built-in LS-DYNA algorithms for hourglass control are used for the fine mesh model (*CONTROL_HOURGLASS keyword).

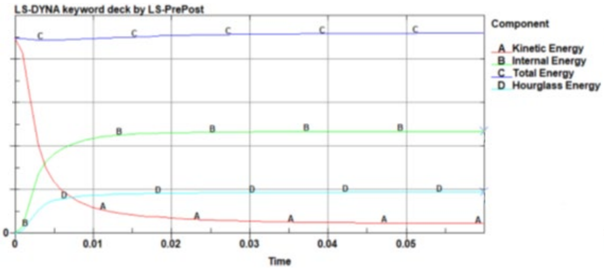

Fig.6: Energy plots - 10cm element size

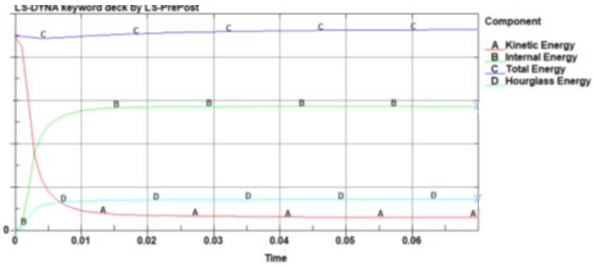

Fig.7: Energy plots - 5cm element size

First, the recommended for high velocity impact, viscosity-based hourglass control IHQ 1,2, with QH=0.1 (recommended in [1][8]) is applied. The respective energy plots are shown in Figure 9. It is observed that the hourglass energy is 25.5% from the internal energy. In other words, the results are the same as those without hourglass control and show that these methods are ineffective for the current study. Figure 8 shows the velocity time-history of the missile which becomes 0m/s at the end of the analysis, i.e. the missile is contained by the slab.

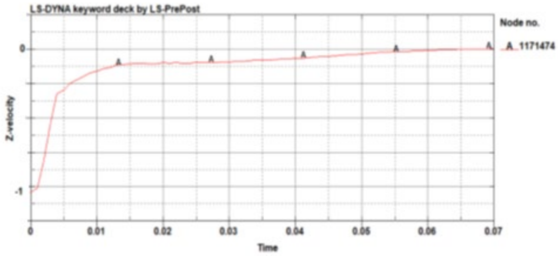

Fig.8: Velocity history – element size 5cm. Control hourglass IHQ 1,2

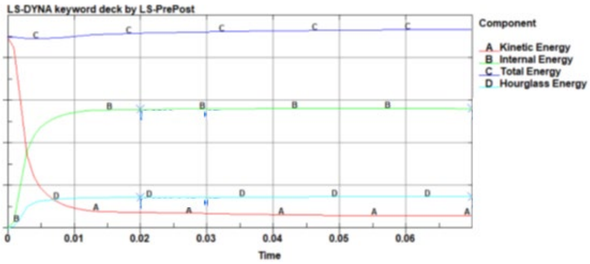

Fig.9: Energy balance- use of control hourglass IHQ 1,2

The results from the stiffness-based control IHQ 4 with QH=0.05 are shown in Figure 10 and Figure 11. Figure 11 demonstrates that the hourglass energy is reduced to 18.4% of the internal energy. It is seen in Figure 10 that the missile velocity at the end of the analysis is greater than 0m/s indicating that the missile perforates the target with some residual velocity.

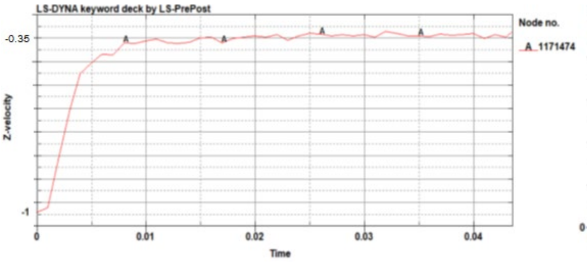

Fig.10: Velocity history – element size 5cm. Control hourglass IHQ 4

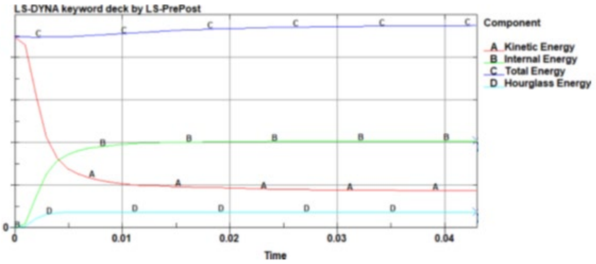

Fig.11: Energy balance- use of control hourglass IHQ 4

The results from control IHQ 6 (recommended by Erhard [9]) with QH=0.1 are shown on Fig.12 and Fig.13. It is observed that the hourglass energy is reduced to 16.8% of the internal energy.

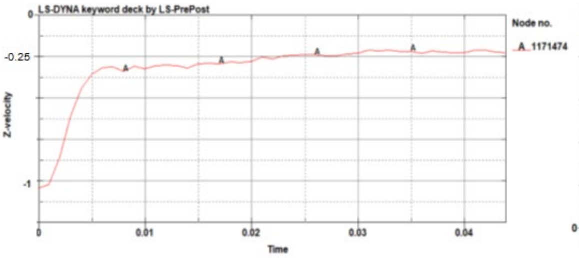

Fig.12: Velocity history – element size 5cm. Control hourglass IHQ 6

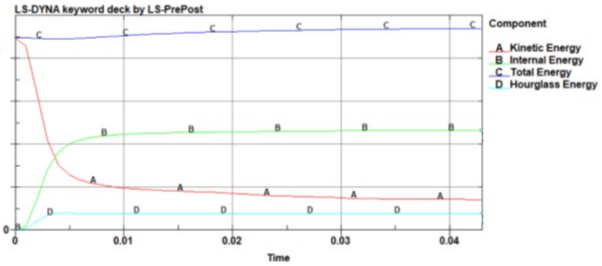

Fig.13: Energy balance- use of control hourglass IHQ 6

Again the hourglass limit of 10% was exceeded, fully integrated solid elements (ELFORM2) are adopted for the model with fine mesh of 5cm. The energy balance of the analysis with fully integrated elements (ELFORM2) is presented at Figure 14. As expected the hourglass energy in this case is zero.

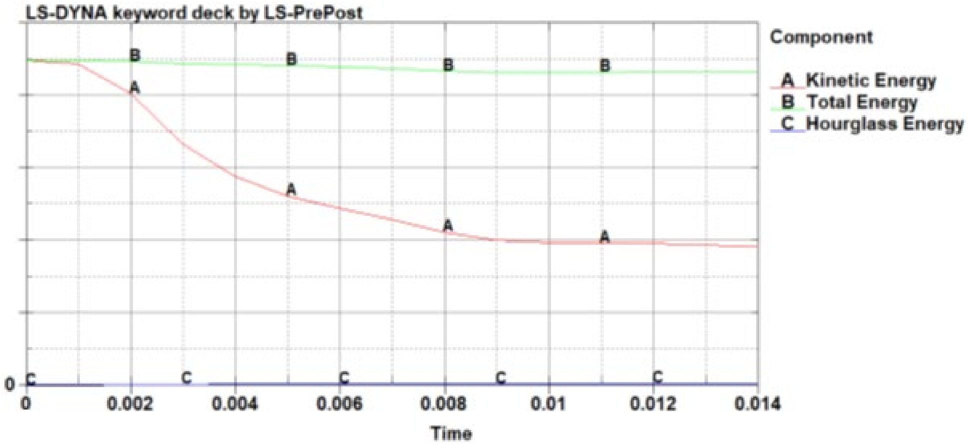

Fig.14: Energy balance- 5cm element size and fully integrated finite elements (ELFORM2)

Figure 15 shows the deformed slab for the calculation with fine mesh and ELFORM1 and Figure 16 shows the deformed slab for the analysis with fine mesh and ELFORM2. The velocity time-histoies of the missile resulting from the two abovmentioned calculations are shown in Figure 17 and Figure 18, respectively. As the plots demonstrate, the analysis with ELFORM1 resuts with missile velocty of 0m/s (can be assumed that the missile is contained by the reinforcement which is not completely ruptured). The analysis with ELFORM2 results with residual velocity greater than 0m/s. Therefore, we decided to verify this result by an analytical calculation, as described in the following section.

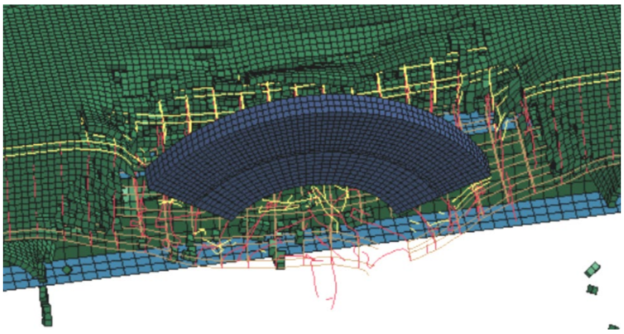

Fig.15: Velocity history - 5cm element size.
Reduced integration (ELFORM1)

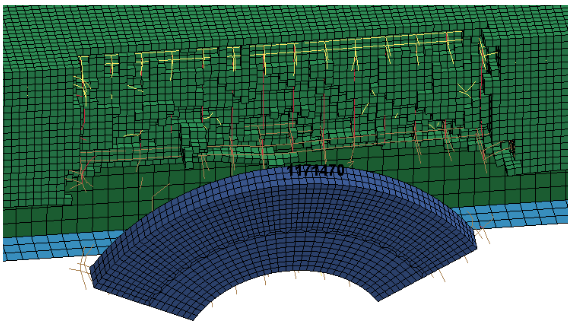

Fig.16: Velocity history- 5cm element size.
Fully integration (ELFORM2)

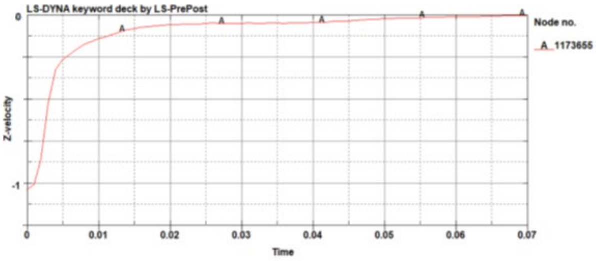

Fig.17: Velocity history- 5cm element size.
Reduced integration (ELFORM1)

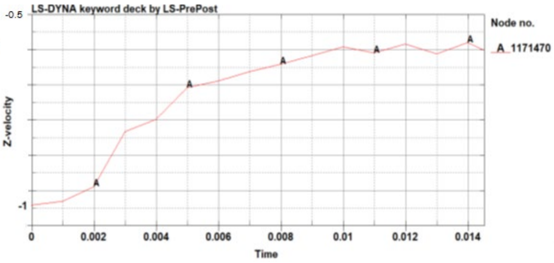

Fig.18: Velocity history- 5cm element size.
Fully integration (ELFORM2)

4 Results based on empirical formula

There are many empirical formulas that can calculate the required scabbing/ perforation thickness of a concrete slab. Reference [3] provides a formula for the residual velocity of a missile that perforates the target structure:

$$v_r = \sqrt{\frac{v^2 - v_p^2}{1 + \frac{M_k}{M}}} \qquad (1)$$

$$v_p = v_a \left[1 + \left(\frac{v_a}{500}\right)^2\right] for\ v_a > 70m/s \qquad (2)$$

$$v_a = 1.3{\rho_c}^{1/6}\sqrt{k_c x 10^6}\left(\frac{p.t^2}{\pi M}\right)^{2/3}\sqrt{\rho_p + 0.3}\left[1.2 - 0.6\left(\frac{c_r}{t}\right)\right] \qquad (3)$$

ρc is the density of concrete (kg/m^3);
ρp is the amount of reinforcement (%) (each face, each way);
t is the plate thickness (m);
p is the perimeter of the missile cross-sectional area (m);
cr is the rebar spacing (m);
M is the missile mass;
Mk is the mass of the ejected concrete;
kc is equal to the unconfined compressive strength of the concrete of the target c f‘c (MPa), when it is less than 37 MPa, and equal to 37 MPa, when it exceeds this value.

Comparison of the missile residual velocity computed by the analytical expression and the velocity obtained from the analysis with most effective hourglass control is shown in Figure 19. The figure demonstrates good match between the analytical and the numerical residual velocity.

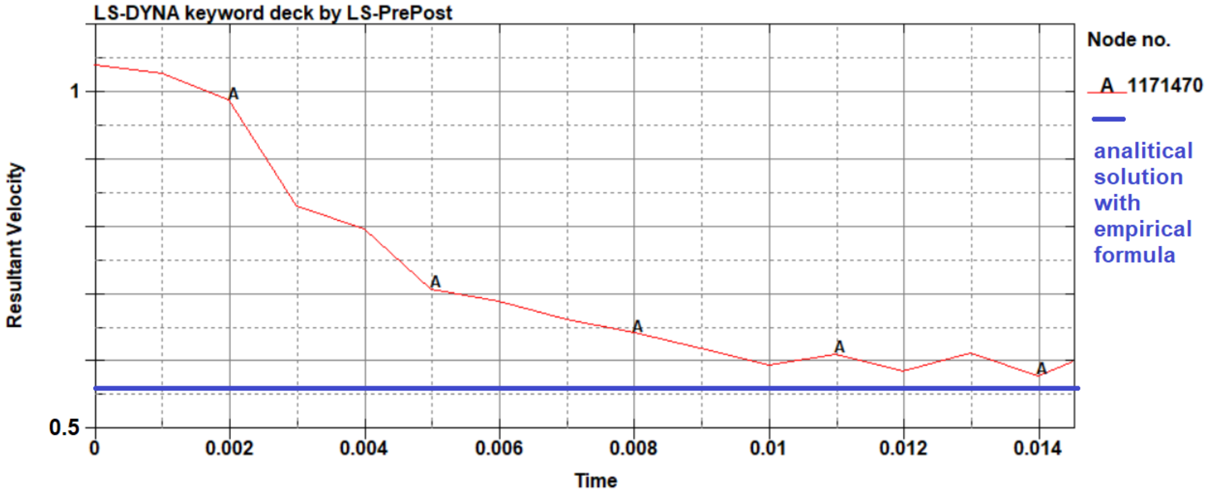

Fig.19: Residual velocity- 5cm element size and fully integrated finite elements (ELFORM2) and analytical solution with empirical formulas

5 Conclusion

The current paper summarizes the assessment of disintegrated turbine disk impacting a reinforced concrete slab. The study is based on missile-target interaction analysis and is consecutively verified with empirical formula used in practice. The mesh refinement study verifies that the element reduction minimizes the hourglass energy and should be applied where deemed reasonable, however even with the refined mesh size the hourglass energy in this study was above the required limit of 10%. The LS-Dyna built-in hourglass control algorithms reduce the hourglass energy but still it remains greater than the assumed limit of 10% of the internal energy. The study demonstrates that the most effective measure for hourglass reduction is the use of ELFORM2 which reduces the hourglass energy to 0. The results presented in the paper demonstrate that the applied measures for hourglass reduction yield different results regarding the missile residual velocity. The cases where the hourglass reduction is ineffective result in the missile contained by the target, i.e. no residual velocity. The cases where the hourglass control measures become effective lead to residual velocity greater than 0m/s, indicating target perforation. The missile residual velocity is the greatest for the analysis case with no hourglass energy. Based on these observations, conclusion can be drawn that effective hourglass control measures need to be considered to derive good verification by an analytical calculation.

6 Literature

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