Response study of concrete gravity dam against aircraft crash

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Abstract
Concrete gravity dam is considered as an critically important mega structure and lifeline of countries with rich water resources. Its failure due to natural and manmade hazard may cause a huge loss of human life and economy. The recent terror attacks involving intentionally crash of aircrafts have raised the safety concern of these critical structures. In the present study, a finite element analysis has been carried out to analyse the behaviour of concrete gravity dams against possible aircraft crash. Reaction-time curve of fighter jet Phantom F4 has been applied on the crest of the dam from upstream face. The Concrete Damaged Plasticity model has been incorporated to predict the behaviour of concrete under high strain loading. It has been found that at a crash speed of Mach 1, fighter jet had caused severe damage to dam. Although the penetration will be small on the loading face of the dam due to massiveness of structure, however, the concrete around crest and neck will fail in tension. Further, redistribution of moments will cause failure of the structure. Maximum deformation has been found to be 8.8 mm. Stresses are quite high at the impact face, however it diminishes at a depth of 8 m from the impact face.

Keywords: Dam, Aircraft crash, Safety, Finite element

1. Introduction
Concrete gravity dams are the important infrastructures for the country because they are generally built for multiple tasks and facilities. Water resource conservation, production of hydroelectricity and flood control in the region are important among all the purposes, for those dams are generally built. The global trend is to construct either concrete gravity dam or arch concrete dam when it is needed to have multiple objectives associated with the project. Hence, one can easily understand the loss to a country associated with the destruction of such important monumental structures. Addition to this scarcity of water is one of the biggest global issues in the present world, which is the key cause for all kind of water disputes among the countries or among
states of countries all over the world [1]. Subsequently, there are possibilities that such large concrete gravity dams can be one of the key targets like nuclear contentment structures of the country for the terrorists or enemy countries and there can be air strike on them. But vulnerability study of concrete gravity dam in this regard still needs attention of the researchers. Although the safety analysis of dam has been studied by many researchers [2-7], however, the issues related to aircraft impact have never been addressed. In the present study, behaviour of concrete dams has been observed for the present warfare situation, though this kind of risk study is relatively new for concrete gravity dams. However, experience of World War II guide us for this kind of study. There are lots of researches have already been done or still going on, on other structures like nuclear contentment buildings for the risk against aeroplane or missile attack on them. But these kinds of studies are much needed for concrete gravity dams as well. The importance of the study would be clearer if we would see the post attack scenario of “Operation Chastise” during World War II, Fig 1. It was an attack on German dams carried out on 16–17 May 1943 by Royal Air Force No. 617 Squadron, subsequently known as the "Dambusters", using a specially developed "bouncing bomb" invented and developed by Barnes Wallis. The Möhne and Eder Dams were breached, causing catastrophic flooding of the Ruhr valley and of villages in the Eder valley, while the Sorpe dam sustained only minor damage. Two hydroelectric power plants were destroyed and several more were damaged. Factories and mines were also either damaged or destroyed. An estimated 1,600 people drowned [8, 9].

It means that ‘failure of dam structure’ and ‘post failure impacts on the region’ both are catastrophic. 9/11 attack on U.S.A. revealed new technique of attack for any kind of monumental or important structure. Direct hit of an aircraft can also be an option for destruction of concrete gravity dam. To understand the response of concrete gravity dam, it is quite complex to do experimental work of aircraft crash on it. Therefore, in the present study analytical technique has been chosen to simulate the problem. The studies, which have been done related to aircraft crash on nuclear contentment structure, can be considered as basis for analytical formulation.

**Table 1.** Configuration of Eder dam

| Eder Dam    |          |
|-------------|----------|
| Construction Started | 1908     |
| Completed    | 1914     |
| Type         | Gravity Dam |
| Length       | 393 meters |
| Height       | 44 meters |
| Base Width   | 36.2 meters |
| Top Width    | 6 meters  |
2 Aircraft loading

Military aircrafts are fast-moving, high responsive and versatile. Among the different variety of military aircrafts, fighter jets are designed primarily for air-to-air combat and air to land target destruction. These jets are proved to be very crucial in all recent military invasions in last few decades. In the present study of safety analysis of dams against possible aircraft crash, fighter jet Phantom F4 has been considered to collide at the neck of the dam structure [10]. With a
maximum velocity twice greater than that of sound, the McDonnell F-4 Phantom was one of the most versatile fighter, multipurpose strike bomber ever built. Although it is the fighter jet started in sixties of last century but still several hundreds of Phantom F4 are in service these days. A brief comparative specification of Phantom F4 with MiG-29 and F16 has been given in Table 2. It may be observed from the table that the Phantom F4 is very much competitive to fighter jets which were quite younger to it in the combat field [11].

Table 2. Comparison of the three fighter planes considered in the study

|                      | Phantom F4 | MiG-29 | F-16 |
|----------------------|------------|--------|------|
| Wingspan(m)          | 11.71      | 13.46  | 9.95 |
| Length(m)            | 19.20      | 22.70  | 15   |
| Height(m)            | 5          | 6.15   | 4.88 |
| Range(Km)            | 3000       | 720    | 4200 |
| Weight(kg)           | 28,000     | 46,200 | 19,200 |
| Max Speed(m/s)       | 650        | 830    | 400  |

In order to simplify the complexity of the finite element analysis through minimising the geometric non-linearity of the aircraft, uncoupled approach of analysis has been adopted. Hence, in the present study, the loading of the aircraft to the containment has been assigned through the well-known Riera's Approach of using reaction-time response curves of the aircraft. Reaction time response curve of Phantom F4 has been calculated in Fig. 2 for three different velocities i.e. Mach 1 (340m/s), Mach 0.735 (250 m/s) and Mach 0.632 (215 m/s). In open literature the conventional design of critical structures had been analysed by using the reaction time curve of the Phantom F4 at a speed of 215 m/s [12]. Hence, in the present study also the same curve has been used as impact load of the aircraft. However, in case of deliberate/ terror attack the aircraft may hit the target with higher speed; consequently, it will cause more disastrous effect. Hence, in the present study, analysis has also been performed for speed of 340m/s.

Fig. 2 Reaction time response of Phantom F4 at different velocities
In effect of an impacting projectile is also a function of the contact area. To simplify the problem, instead of providing a time dependent contact area (starting from a contact point, increasing to a circle and finally to a bird-shaped contact area) an equivalent circular area has been assumed in the present study. The force history curve of the aircraft was assigned to the dam at a given constant area equivalent to the average of total cross-sectional area of its fuselage and wings. This hypothesis has been emerged as a common and frequent opinion in available literature [13-18] has followed the same hypothesis. Accordingly, the impact zone of Phantom F4 was considered as a circular region of $\phi$ 6 m as discussed above. The reaction force after dividing with the contact surface area has been assigned to respective location, depicted in Fig. 4. The reaction force history was thus transformed in to pressure versus time curve varying in time domain.

3. Finite element modelling

The concrete gravity dam section considered for the modelling and simulation in this study is a 3-dimensional model of a typical monolith of concrete gravity dam with thickness about 20m. The geometrical configuration of the dam is considered similar to the geometrical configuration of tallest non-overflow monolith of Pine Flat dam [19]. Geometric parameters are presented in Fig. 3.

![Geometric configuration of Concrete Gravity Dam considered in the study](image)

**Fig. 3** Geometric configuration of Concrete Gravity Dam considered in the study
In the present study, finite element tool Abaqus/Explicit [20] has been used to develop the model of the dam section. The finite element discretization of the dam section has been shown in Fig. 4. Continuum three-dimensional eight nodded reduced integration element (C3D8R) elements are adopted for discretization of elements. The selected impact zone at crest (фи6m) has been decided to have eight number of element along the thickness through a mesh convergence analysis. Remaining body of the dam section has been modelled with coarser elements; in order optimise the total number of element. In the present analysis, there are 6367 elements with 6599 nodes. Elements are having aspect ratio near one in the impact zone; however, away from impact zone aspect ratio may have some larger values.

4. Constitutive material model and properties

Prediction of behaviour of any structure through the finite element solver is a function of the material model opted in the analysis. Many concrete material models have been programmed and incorporated in these solvers. For concrete material models, damage and plasticity are two important features where researchers concerned. In ABAQUS, concrete damaged plasticity model (CDP) [21, 22], is widely used among researchers [23-26].In the present study also, the concrete damage plasticity model of Abaqus [20] material library was used for the simulating the behaviour of concrete in the containment structure. It is a phenomenological model which can be executed both in Abaqus standard as well as explicit analysis techniques. The material incorporates the plastic behaviour of the concrete both in compression as well as in tension. The model uses the concept of isotropic damaged elasticity in combination with isotropic tensile and...
compressive plasticity to represent the inelastic behaviour of concrete. It can effectively be used for plain concrete even though it is intended primarily for the analysis of reinforced concrete structures subjected to monotonic, cyclic, and/or dynamic loading. The model has the provision to use strain rate dependent behaviour of the concrete. The material parameters used to predict the behaviour of concrete are presented in Table 3.

| Material properties of concrete |
|--------------------------------|
| Density, \( \rho \) (kg/m\(^3\)) | 2400 |
| Modulus of elasticity, \( E \) (N/m\(^2\)) | 2.7386E+10 |
| Poisson’s ratio, \( \vartheta \) | 0.17 |
| Dilation angle, \( \psi \) | 30 |
| Eccentricity | 1.0 |
| Initial equi-biaxial compressive yield stress to initial uniaxial compressive yield stress, \( f_{b0} / f_{c0} \) | 1.16 |
| Bulk Modulus, \( K \) | 0.666 |
| Fracture Energy, \( G_f \) (N/m) | 720 |
| Uniaxial Failure Stress (Tension), \( \sigma_{f0} \) (MPa) | 10.8 |
| Cracking displacement, \( U_{to} \) (m) | 0.0001332 |
| Tensile strength, \( \sigma_{st} \), MPa | 3.86 |
| Compressive Strength, MPa | 30 |

5. Results and discussion
A three-dimensional numerical modelling of a concrete dam has been performed through the finite element solver Abaqus. Fighter jet Phantom F4 has been considered to crash at a speed of mach1 near the crest of dam from upstream side. The deformations in the direction of the loading are plotted in the Fig. 5. The deformation has been found to be localised in the crest. The maximum deformation has been found to be 8 mm in the impact zone itself. However, the effect of crash was comparative low at the downstream face of the dam. Moreover, near the toe and heal of the dam there is no effect of crash due to massiveness of the structure. Tension damage in the concrete has been plotted in Fig. 6. The damage of the material under tension or compression has been assumed to occur when the corresponding damage parameter, \( d_t \) or \( d_c \) respectively, has reached a value of 0.99. The value of the damage parameter varies from 0 to 0.99 for undamaged and complete damaged material respectively. It can be visualised that the damage occurred is very widespread in and around the crest of the dam. The damage experienced by the concrete under
tension will be highlighted more effectively with removal of fully damaged elements from the
dam. In Fig. 7, different directional views of dam crest with removal of completely damaged
elements have been shown. From the damage pattern reported in Fig. 7, a very good resemblance
can be found with the case reported in Fig.1 i.e. Eder dam failures. Only few elements of the crest
neck have been noticed undamaged in the current study. However, a redistribution of moment
may lead to overturning of the above neck portion of the dam.

Fig. 5 Deformation along the direction of loading

**Fig. 5** Deformation along the direction of loading

Fig. 6 Tension damage in concrete

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As the behaviour of concrete is better in compression always, the compressive damage however is observed to be of lesser intensity. To review the compression and tension damage across the cross-section of the dam, damage contour plots of vertical cross-section have been shown in Fig. 8. Tension damage is more visible at the D/S side of the crest. However, in case of compression damage, complete failure of elements has not been reported.

Fig. 7 Dam head after removal of completely damaged concrete element

Fig. 8 Damage along the longitudinal cross-section of dam (a) Tension (b) Compression
The contour of maximum principle stresses has been plotted in Fig. 9. High concentration of compressive stress has been reported at the point of impact. A maximum compressive stress of magnitude 11.56 MPa has been observed at the centre of impact. However, patches of tensile stresses of greater than 2 MPa has been found on both the upstream and downstream face of the dam. To analyse the stress distribution across the thickness of dam, a nodal path from the centre of impact to the downstream face has been chosen as shown in Fig. 10(a). High stresses have been reported at the u/s face i.e. at the impact face, Fig. 10(b). Stresses have die down to a negligible value at a depth of 8 m inside the dam thickness. The maximum stress in the direction of loading (S\textsubscript{11}) has maximum value of 38 MPa at the face of crash.

Fig. 9 Contour profile of maximum principal stress

Fig. 10 (a) Path selected (b) Stress distribution along the selected path
6. Conclusions
A three-dimensional finite element simulation has been carried out using Abaqus/Explicit. A
typical concrete gravity dam model similar to Pine Flat Dam has been developed. Aircraft loading
has been applied with the help of Riera’s Reaction time approach. A normal hit at the crest of dam
from the upstream side has been considered. Deformation/ displacement has been found to be
very confined in the impact zone. However, the crest of the dam has been damaged under tension.
Tensile damaged was more visible on the opposite i.e. downstream face of the dam.

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