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PREDICTIONS OF DAMAGE TO BUILDINGS BY DEBRIS

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Impact by debris is a major cause of damage to buildings in hailstorms, windstorms and rockfalls. The effects of the impact need to be quantified so that protective installations including building facades, roof coverings and other forms of built installations that are exposed to the hazard, can be designed or retrofitted to withstand projected hazards in a rational and economical manner. This research covers this type of hazards in order to address the lack of information on physical properties of common debris materials, lack of guidelines on how to obtain reliable predictions of the impact, and the poor understanding of the fundamentals. The new knowledge and methodology to be developed in this poorly informed and understood area of technology should instill a new perspective to every engineer in their daily practices. Ultimately, a better understanding and quantification of impact forces would enable the development of innovative protective systems.

Keywords: Storms, Hail, Impact, Rockfalls.

1 INTRODUCTION

Most structural analyses in a contemporary design office are done by computer, performing electronically most tasks that were once done manually. While this makes sense in view of improved efficiency, fewer engineers are now able to evaluate results reported by advanced computations, including those to assess the effects of blast and impact. The common strategy adopted by vendors of computational tools is offering users a "total solution" to the problem in one analysis (e.g., Timmel *et al.* 2007; Fan *et al.* 2011). In a total solution, every detail of stresses, strains and deformation are reported, and this requires full details of both the target and the impactor. The simulation outcome of the total solution is a 4D display of how the damage would evolve in the course of the event, along with the 3D image of the damaged component requiring repair.

This type of simulation is certainly appealing to the eye, but its validity as a model is not reflected in its appearance. The merit of a model is in how it behaves, not how the solution is presented. The onus is on the user to type in all the correct instructions into the program. The literature offers little help in this regard, given that articles which present results of analyses do not usually provide a listing of input parameters that have been keyed in along with explanations of the choice of the values. The myth held by many designers and stakeholders is that the accuracy of the solution to an analysis is controlled by the capability of the software.

In reality, the accuracy of a solution is limited by (a) assumptions made in the analysis, and (b) the knowledge required for input into the software. Adopting a powerful software can be counter-productive if knowledge on the input parameter is lacking. On the other hand, the more that is understood about the underlying phenomena, the simpler the analysis. As for many methods of analysis in the field of solid mechanics, predictive relationships originally derived from first principles can be simplified to address what matters most, while accepting some errors. Acceptable solutions for impact actions can be derived from first principles too, or modified from existing expressions to take into account the effects of key influential factors.

An impact action can be resolved into the global deflection demand (i.e., impulsive effects) of the impact and the localized contact force. It has been shown that the deflection of an element (e.g., a column) resulted from the impact can be calculated by the use of fairly simple algebraic expressions (Ali *et al. 2*014). An equivalent static force could then be applied to generate deflection to match with estimates. Stresses, strains and deformation so obtained from the static analysis could then be taken as a solution to the impulsive effects of the impact.

The contact force value is another critical piece of information, for it controls the piercing of metal cladding or the probability of damage to glazing facades. However, common calculation methods based on energy principles can only be used to quantify the impulsive effects of the impact but *not* the contact force. The harder the impactor material, the shorter the duration of contact, and hence the higher the amplitude of the contact force in delivering a given amount of momentum from the impact.

The rest of the paper is divided into two parts: (a) introducing the modified energy approach for obtaining realistic estimates of the impulsive effects of the impact and (b) introducing expressions for calculating the magnitude of the transient force developed at contact between the impactor and the surface of the target.

2 IMPULSIVE EFFECTS OF IMPACT

For estimating the impulsive effects of an impact the following relationship was derived by considering the principles of equal momentum before and after contact is made (as represented by the terms to the left and right of the equal sign respectively), as shown by Eq. (1):

$$m v_0 = (\alpha m) v_2' - m v_1' \tag{1}$$

where m is the mass of the impactor, v_o is the incident velocity of the impactor, αm is the generalized mass of the targeted element, v_2' is the velocity of the target following impact, v_1' is the velocity of the impactor on rebounce in opposite direction.

Eq. (1) is strictly speaking only valid for impact between two free bodies in space, and can be adapted for cases where the targeted body is not a free body but supported by a spring that has a stiffness value to emulate the behavior of a simply-supported beam, as depicted in Figure 1:

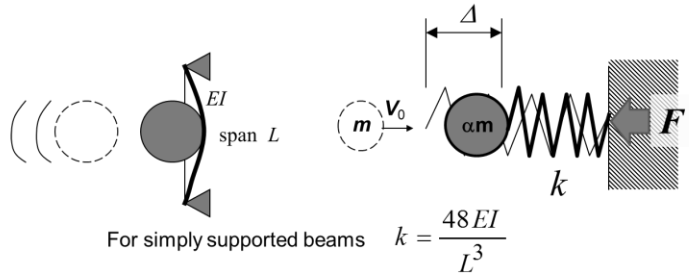

Figure 1. Spring-connected lumped mass model for analysis of impact action.

Given the *Coefficient of Restitution* (COR) of the impact is defined by Eq. (2):

$$COR = \frac{v_1' + v_2'}{v_0} \tag{2}$$

The velocity ratio, and the kinetic energy ratio of the impact (which is indicative of energy losses) is accordingly obtainable from Eq. (3) and (4) respectively for cases where the impactor does not become embedded into the surface of the target following the impact.

$$\frac{v_2'}{v_0} = \frac{1 + COR}{1 + \alpha} \tag{3}$$

$$\frac{KE_2}{KE_0} = \frac{\frac{1}{2}\alpha m.\left(v_2'\right)^2}{\frac{1}{2}m.(v_0)^2} = \alpha\left(\frac{1 + COR}{1 + \alpha}\right)^2 \tag{4}$$

Eq. (4) can be modified as follows to incorporate parameter λ, which is either equal to 1 (to represent the effects of an embedded impactor), or 0 for cases where the impactor is detached from the target:

$$\frac{KE_2}{KE_0} = (\lambda + \alpha)\left(\frac{1 + COR}{1 + \alpha}\right)^2 \tag{5}$$

The deflection of the target and the corresponding equivalent static force (or reaction force) is obtainable using Eq. (6a) and (6b):

$$\Delta = \frac{mv_0}{\sqrt{km}}\beta \tag{6a}$$

$$F = v_0\sqrt{km}\beta \tag{6b}$$

The value of β is therefore given by Eq. (7) which takes into account the effects of both the mass of the target and the coefficient of restitution (COR).

$$\beta = \sqrt{(\lambda + \alpha)\left(\frac{1 + COR}{1 + \alpha}\right)^2} \tag{7}$$

Eq. (7) is reduced to Eq. (8) for the idealized conditions of inelastic impact of an embedded impactor (COR = 0 , λ = 1) as presented in Ali *et al.* (2014).

$$\beta = \sqrt{\frac{1}{1 + \alpha}} \tag{8}$$

Consider an impactor that has mass equal to one-fifth of the generalized mass of the target (e.g., an RC column): $\alpha = 5$, the deflection demand, and an equivalent force, generated by the impact, is only about 0.4 times of that. This is estimated by simply equating kinetic energy with elastic strain energy, as is normally the approach adopted by current codes of practices (e.g., AS5110.2 2004; BSI 2008; AASHTO 2012). Thus, an estimated deflection of 100 mm is reduced to 40 mm. The deflection is increased slightly to 45 mm if there is a small amount of re-bounce (COR = 0.2) of the impactor according to Eq. (7). An equivalent static force is then applied to generate a deflection that matches those estimated from energy principles. These estimates can be obtained conveniently through the expressions presented above. Importantly, the accuracies of these estimates have been verified by comparison with results from both finite element analyses and physical experimentation on miniature scale models (Ali *et al*. 2014). Without these expressions, it would have taken much effort to set up elaborate finite element models for obtaining total solutions from the so-called state-of-the-art software.

The estimated contact force values can be applied to tile specimens and glazing panel specimens on a normal test rig, to assess the risks of potential damage to these components in projected impact scenarios. It would have been a great deal more costly to test these specimens dynamically when the amount of force to be applied is uncertain.

3 LOCALIZED EFFECTS OF IMPACT

The much higher amplitude, shorter duration contact force can be determined by considering the impactor as a lumped mass connected by a spring to half-space (in a single-lumped mass system), or to another lumped mass representing the target (in a two-lumped mass system). The hardness of the impactor and the surface of the target is reflected in the stiffness of the connecting spring in the lumped mass model. The maximum contact force associated with a given amount of absorbed energy depends on the hysteretic relationship adopted in the modelling. The simplest hysteretic contact model is that of linear elastic behavior which has neglected the well-known stiffening behaviour of contact. The alternaive non-linear elastic model is consistent with observations of quasi-static testing on the impactor and the surface of the target. It is consistent with Hertz Law in which the value of p is taken by default as 1.5. By contact mechanics based on Hertz Law, the value of contact force (F_c) generated by a rigid sphere indenting into the surface of a half-space made of materials of Young's modulus (E) is defined by Eq. (9a) – (9c).

$$F_c = k_n \delta^p \tag{9a}$$

where:

$$k_n = \frac{4}{3} E \sqrt{R} \tag{9b}$$

$$p = 1.5 \tag{9c}$$

Substituting Eq. (9b) and (9c) into (9a) gives $4/3 \times 20\sqrt{0.25} = 13$ GN/m^p based on treating the debris piece as a spherical object. The maximum contact force is accordingly found by the use of Eq. (10).

$$F_{c\max} = k_n \left(\frac{p+1}{2k_n} m v_0^2 \right)^{\frac{P}{P+1}} \tag{10}$$

where m is the mass of the impactor and v_0 the incident velocity of impact.

Substituting the value of k_n = 13 GN/m$^{1.5}$, p = 1.5, m = 160 kg and v_0 = 6.3 m/s^2 into Eq. (10) gives a maximum contact force value of approximately 2400 kN. This method of estimating contact force provides a first-cut estimate for low-velocity impact scenarios where the value of E of the impactor and the surface of the target are known. Improved estimates for the value of the maximum contact force can be found in Sun (2015).

4 CONCLUSIONS

This paper presented simplified methods for analyzing the effects of impact by a solid object based on resolving the action into (a) the impulsive component, which results in the deflection of the target and the associated bending moments and shear forces, and (b) the contact force component, which results in localized damage such as indentation into the surface of the target and perforation. Algebraic expressions were first presented for estimating the deflection demand of the target, and hence the quasi-static force, for given impactor mass, incident velocity of impact, mass ratio, and coefficient of restitution. The presented expression takes into account the significant mitigating effects of the target mass, and provides much more accurate predictions than existing relationships that are currently used in highway codes of practices. The analytical procedure is generic in nature and can be used for assessing the risk of failure of a piece of tile, a glazing panel, or a concrete member subject to impact by a solid object. A separate set of expressions was later presented for modeling contact force, which is of much higher amplitude than the quasi-static force. The important influence of the hardness of the impactor object (and that of the surface of the target) has been taken into account.

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