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Damage modelling of aluminium panels impacted by windborne debris

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ABSTRACT

Impact by flying debris in windstorms conditions has been a major contributor to damage to aluminium and other types of building facades. The damage so caused to cladding panels was mainly controlled by the amount of force that was developed at the point of contact between the debris object and the surface of the target. However, no codified design guidelines are currently available to quantify the required impact resistance of an aluminium panel for given storm scenarios. Current analytical expressions derived for analysing impact actions as reported in the literature are mostly based on the use of energy principles. The influence of the hardness of the debris object and the magnitude of the contact force has not been taken into considerations. Thus, the amount of deformation that is inflicted on the panel by the impact of a non-rigid projectile object can be overstated. This paper presents an analytical expression that has been developed for estimating the severity of damage to the surface of a cladding panel (and to determine if leakage of rainwater from the panel can be resulted) for given mass of the debris object, velocity of impact, and importantly, parameters characterising the stiffness properties of the impactor object.

1. Introduction

Flying debris generated in extreme weather conditions such as windstorms and cyclones are of concern to property owners and stakeholders because of widespread damage to building facades including roofs, doors and window shutters. Glazing facades and metal claddings have been identified as the most vulnerable type of elements sustaining damage (Minor, 1994). Further, impact by hailstones on roof coverings and many other exposed installations has also caused a colossal loss during the past few decades (Changnon, 2008; Changnon et al., 2009). Impact of debris material or hailstones on a metal cladding can cause perforation which will result in the ingress of water into the building, or permanent deformation which jeopardize the appearance of the building. The total cost of replacing dented or perforated panels in the aftermath of a severe storm affecting a major city can be up to tens of millions of dollars (Sparks, 2003; Sparks et al., 1994). For example, the damage bill of a windstorm event in Queensland in 2008 was in the order of AUD 500 M.

Predicting damage by impact action is not a simple procedure as it is dependent on both the material behaviour and structural dynamic behaviour of the impactor and that of the target. Impact between the two objects can be resolved into impulsive action and localized contact action. An impulsive action causing global deflection demand on the target such as bending, or overturning, can be emulated by the use of a quasi-static force, the magnitude of which can be estimated by employing equal momentum and energy principles (Ali et al., 2014). In contrast, the impact action which is applied at the point of contact lasts for only a few milliseconds and is responsible for localized damage such as denting, or perforation (Yang et al., 2014).

In the past few decades, significant amount of effort has been devoted to developing analytical and numerical methods for determining the deformation of the aluminium panel surrounding the point of contact (Alphonso and Barbato, 2014; Calder and Goldsmith, 1971; Mohotti et al., 2013). Sophisticated finite element software packages such as ABAQUS and LS-DYNA have been used by engineers to circumvent the need for conducting costly dynamic testings (Chen et al., 2014; Herbin and Barbato, 2012; Liu et al., 2014; Mohotti et al., 2013; Raguraman, 2008). However, the accuracy of the FE model relies on the meshing of the target surrounding the point of contact and the assumed dynamic properties of both the impactor and the target (Cheng et al., 2001). An important drawback of numerical modelling when applied in practice is the high computational time required for completing an execution coupled with the need to undertake repetitive analyses for tracking the sensitivity to changes in value of the input variables. Amid uncertainties of the modelling parameters and computational time, analytical predictive models are always valuable.

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Reviews presented in the literature on theoretical investigation of damage caused by windborne debris on aluminium panels were based on certain yield criteria or energy principles. Little attention has been devoted to quantifying the contact action generated by the impact (Christoforou et al., 2013; Jones, 2012; Levy and Goldsmith, 1984; Zheng and Binienda, 2007). A generic expression which was originally introduced by Duffey (1967) based on energy principles for estimating the permanent deformation of the aluminium plate when struck by a rigid spherical impactor was modified by Calder and Goldsmith (1971) in which linear strain hardening has been incorporated into the model as shown in Eq. (1). It is noted that Eq. (1) is essentially in the quadratic form if w_o^2 is taken as a variable.

$$w_o^4 + \frac{16\sigma_y}{a^2\alpha}w_o^2 - \frac{32(1-v+v^2)^{0.5}}{a^2\alpha\pi h}(\Delta KE) = 0 \tag{1}$$

where, w_o is the permanent deformation at the point of impact, σ_y is initial yield stress, α is linear work hardening parameter, v is Poisson's Ratio, h is half thickness of the plate, ΔKE is the amount of energy absorbed by the deforming plate, and a is a constant.

Mohotti et al. (2013) developed the analytical procedure further by incorporating non-linear strain hardening behaviour of the aluminium. Results so obtained from the procedure were used for comparing with results from experimental investigations and numerical simulations involving program LS-DYNA. It is noted that there has been no considerations on modelling the influence by the hardness (or stiffness) of the impactor which in turn controls the contact action. The typical assumption to make in those studies was that the total amount of kinetic energy delivered by the impact was fully absorbed by the plate undergoing permanent deformation. For non-rigid projectiles the amount of deformation of the aluminium panel can be over-predicted by analytical models that are currently available because a significant amount of energy can be taken up by the impactor object absorbing energy through its own deformation. At present, no reliable simulation procedure is in place to predict damage on cladding panels with a good degree of accuracies.

This study presents an analytical model that has been developed for predicting deformation, and damage, to an aluminium panel based on correlating the magnitude of the contact force with the compressive stiffness of the impactor object. Impact experiments and computer simulations that have been undertaken in the study were based on idealising a debris object into a spherical specimen for two reasons: (i) results can be easily reproducible in the future as every details of the impactor specimens that are relevant to the impact actions can be documented (ii) the contact force value measured from an impact experiment of a spherical specimen (of gravels and simulated hail ice) has been found to be consistently very close to the value of the mean contact force of non-spherical specimens derived from the same material when the impact parameters have been held constant (as evidenced from findings in a previous study (Perera et al., 2016)). Further investigations have also been undertaken to determine the threshold velocity of impact of a 62.5 mm diameter impactor object to perforate a 2 mm thick aluminium alloy panel. The findings of this study can also be successfully implemented in estimating damage to metal roofings for vertical impact of hail when the compressive stiffness properties of the hailstones are known.

2. Analytical expressions for estimating permanent deformation

2.1. Evolution of the predictive model

The expression originally proposed by Duffey (1967) for predicting the amount of permanent deformation inflicted by the impact of a flying object on an aluminium plate has been modified by Calder and Goldsmith (1971) to take into account the effects of strain hardening as shown by Eq. (1). The expression has been further developed, and verified, by Mohotti et al. (2013) to incorporate non-linear strain hardening behaviour of the aluminium material. The modified relationship which has replaced the rate of strain hardening α by parameters B and n for characterising non-linear behaviour of the plate as per recommendations by Mohotti et al. (2013) is shown by Eq. (2).

$$w_o^{2(n+1)} + \frac{2^{n+1}\sigma_y(n+1)^2}{a^{2n}B}w_o^2 - \frac{2^{n+2}(n+1)^2(1-v+v^2)^{0.5}}{a^{2n}B\pi h}(\Delta KE) = 0 \tag{2}$$

where, B and n are strain hardening parameters, the values of which can be obtained from testing at high strain rates.

Eq. (2) has been simplified further as follows:

Eq. (3) was obtained by multiplying every term in Eq. (2) by the factor of $\frac{a^{2n}B}{2^{n+1}\sigma_y(n+1)^2}$.

$$\frac{a^{2n}B}{2^{n+1}\sigma_y(n+1)^2}w_o^{2(n+1)} + w_o^2 = \frac{2\times(1-v+v^2)^{0.5}}{\pi h\sigma_y}(\Delta KE) \tag{3}$$

Eq. (3) can be reduced to the following form:

$$w_o^2\left[1+\frac{a^{2n}B}{2^{n+1}\sigma_y(n+1)^2}w_o^{2n}\right] = \frac{2\times(1-v+v^2)^{0.5}}{\pi h\sigma_y}(\Delta KE)$$

It is noted that the term $\frac{a^{2n}B}{2^{n+1}\sigma_y(n+1)^2}w_o^{2n} \ll 1$ for aluminium alloy. The relationship is then simplified further into Eq. (4).

$$w_o = \sqrt{\frac{2\times(1-v+v^2)^{0.5}}{\pi h\sigma_y}(\Delta KE)} \tag{4}$$

Eq. (4) has also been presented as a simplified version of Eq. (1) in Levy and Goldsmith (1984).

With every analytical expression presented in the above the total amount of energy absorbed by the deforming plate (ΔKE) is assumed (erroneously) to be equal to the kinetic energy delivered by the impact. Thus, the portion of energy expended in deforming the impactor object has been neglected. As a result of the idealisations, the amount of deformation predicted by this expression is much higher than the experimentally measured values.

In this investigation, the analytical equation proposed by Mohotti et al. (2013) for predicting permanent deformation of an aluminium plate as shown in Eq. (2) is modified to take into account the effects of the hardness of the impactor object.

2.2. Incorporating stiffness properties of the impactor as parameters

Contact force (F_c) generated by the impact of the projectile object can be estimated using the non-linear visco-elastic contact model as defined by Eq. (5) and Fig. 1a.

$$F_c = k_n\delta^p + D_n\delta^p\dot{\delta} \tag{5}$$

where,δ is the deformation of the projectile, $\dot{\delta}$ is the deformation velocity, $D_n = (0.2p + 1.3)\left(\frac{1-COR}{COR}\right)\frac{k_n}{\dot{\delta}_0}$, COR is the kinematic coefficient of restitution, $\dot{\delta}_0$ is the initial deformation velocity, and k_n and p represent the dynamic compressive stiffness behaviour of the impactor object.

The amount of energy dissipated within the impactor object in the course of the impact is represented by the (hatched) area enclosed in between the line of loading and unloading (Fig. 1a) and can be approximated by the area of a triangle (Fig. 1b) as represented by Eq. (6).

$$KE_{Fc} = \frac{1}{2}\times F_{cmax}\times\delta_{max} \tag{6}$$

where, F_{cmax} is the maximum contact force and δ_{max} is the maximum deformation.

It is noted that the accuracy of the presented approximation procedure based on idealising the hysteretic loop of the impactor