The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Estimation of impact forces generated by storm debris

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ABSTRACT

Storm debris including hailstones have been causing very costly damage to both metal and tiled roofs in regions of temperate climate. Few guidelines for assessing the vulnerability of existing installations have been developed. Consequently, it is difficult to obtain reliable estimates of the risks of damage for a given storm scenario in order to plan for retrofitting work for reducing damage in the future. Numerical simulations are common but never adequately validated by physical experimentations. There is a lack of integrated use of analytical tools in conjunction with experimentation techniques which are underpinned by an understanding of the fundamental principles. Although the idea of dynamic modelling by two-degree-of-freedom (2DOF) lumped mass model is well known, there are plenty of scopes for further developments for improving the accuracies of the modelling. A new calibration procedure involving the use of a custom made experimental device has been developed for determining the dynamic compressive stiffness properties of impactors such as debris and hailstones for which no material model exists. A diversity of impact scenarios for common spherical objects have been modelled using this newly developed procedure. The methodology is amenable to practical applications which waives off the need of exhaustive experimentations.

1. INTRODUCTION

Hailstones and wind borne debris have been identified to be accountable for over a third of the total insured loss from all forms of natural disasters in Australia. Roofs covered by Terracotta tiles and steel sheets have been found to have sustained most of the damage in a hailstorm whereas glazing facades and steel claddings tend to be most vulnerable to damage by wind borne debris. Damage statistics based on data collected from recent events in Australia are summarised in the next section.

Unlike blast actions the impact action of a solid object cannot be pre-defined as much depends on the interaction between the impactor and the target. In addition, high contact force generated by a high speed impact can result in perforation or denting of

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the target. Steel sheets used in rooftops and cladding are most susceptible to this type of damage. Meanwhile, high reaction force and the associated internal stresses can result in the fracture of brittle materials like roof tiles and glass panes which typically fail by flexural tension resulted from out-of-plane bending. The estimation of bending moment and deflection is based on considering the impact action as a quasi-static force (also known as the reaction force). The distinction between the contact and reaction forces in the context of impact actions is not widely understood and few guidelines have been developed for their estimation. There are also challenges with computer simulations amid lack of knowledge and uncertainties over the compressive loading-unloading properties of the impactor (namely debris and hailstones). Whist experimentations involving the use of the gas gun is common the amount of potentially useful information that has been retrieved from those experiments is very limited. Experimental data on contact force in particular is very scarce because of challenges over accuracies of measurements.

The modelling of quasi-static (reaction) force and the associated flexural actions is the focus of Section 3. The interesting, and important, model which characterises the effect of the size of the target is illustrated by examples of impact on beams and plates. A new tubular device that has been developed for measuring contact force is introduced in Section 4. It is now possible to accurately identify the non-linear inelastic compressive stiffness of the debris material by the use of this custom made apparatus along with a calibration procedure. Given the compressive stiffness properties, the amount of contact force generated by a range of impact scenarios involving the same type of debris can be estimated reliably using analytical simulations.

In summary, the calculation and experimental techniques introduced in this paper will enable accurate predictions of impact actions to be made of storm debris for checking the design of fragile items to ensure that they perform within the threshold of damage. Much of these techniques are new as they are unique to the scenarios of projectile (and dropped object) impact which has been attracting relatively little attention on fundamental research and are distinct to actions by strong wind and blast pressure.

2. DAMAGE STATISTICS AND LITERATURE REVIEW

Natural disasters such as earthquakes, bush fires and flash flooding have been attracting most of the publicity and attention by authorities because of the heavy casualties inflicted by such events. In comparison, damage caused by hailstorms has been receiving relatively little attention by the media because of the typically lower number of fatalities even though hailstorms account for over a third of the total insured loss from all forms of natural disasters in Australia (Schuster et al., 2005). Of the top ten most costly natural disasters in Australian history five of them were hailstorms. Despite this there is a glaring lack of knowledge on hailstorms and their impact on built infrastructure (Crompton & McAneney, 2008). The 1999 Sydney hailstorm had a total damage bill of AUD $2.2 billion in a single event (EMA 2007) with insured losses reaching AUD $1.7 billion. In this storm approximately 60% of the AUD$1.7 billion insured loss was paid out for damage to property, 29% to motor vehicles and 6% to aircrafts. The direct physical impact of hailstones accounts for 80% of the total damage. Ingress by water ingress accounts for the remaining 20% (Andrews & Blong, 1997).

The size of a hailstone has been established as the most important parameter characterising its damage potential given the correlation between size and terminal velocity in conditions of free fall (Changdon, 1977). In a review of ten independent studies on the correlation of the terminal velocity of the hailstone and its size a terminal velocity of 15 – 25 m/s was projected for hailstones of size 20mm, and 25 – 40 m/s for size of 50mm (Darling, 2012).

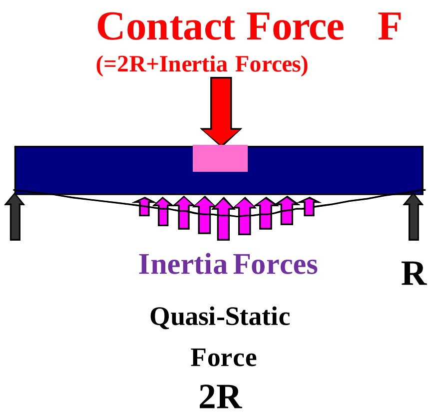
Terracotta tile roofs are by far most vulnerable and account for over 70% of roofs requiring repair after hailstorms according to Emergency Management Australia's disaster database (EMA 2007). Given the prevalent use of this type of tiles for roof construction in domestic buildings this trend is expected to continue. The threshold size of hailstones for tile damage is approximately 5cm in diameter as revealed by data from TORRO (2006) from the UK in combination with Australian data collected by SGIO (2004) which is a subsidiary of the Insurance Australia Group. This finding is re-affirmed by the independent report by Yeo et al (2000) on damage to car roofs. Hailstones exceeding this size are likely to break roof tiles compromising the water tightness of roofing systems.

Glass façade panels have been identified to be the most vulnerable building element to damage by windborne debris (Minor, 2005). Research into windborne debris trajectories, and hence velocity, has been undertaken by Tachikawa (1988) in which the ratio of aerodynamic forces to gravity was proposed as a modelling parameter. A more comprehensive model for debris trajectories has also been developed by Lin, Holmes & Letchford (2005, 2007). Study has also been conducted for assessing the performance of steel cladding material when subject to the denting actions of windborne debris. Fragments of broken terracotta and concrete roof tiles can also become windborne debris as evidenced by observed damage in hurricanes on the east coast of the United States (Minor, 1994). This compounding impact of hailstones and strong wind is well illustrated by the 1999 Sydney hailstorm which resulted in a fourfold increase of damage from that caused by the 1986 Sydney hailstorm striking the same area (Crompton & McAneney, 2008).

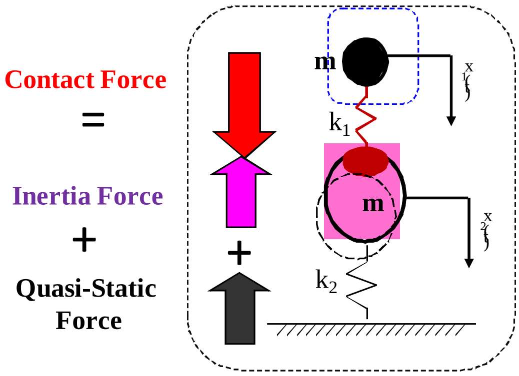
Research into windborne debris on building materials provides additional insight into the performance of steel cladding in severe windstorms. The most recent (2011) edition of the Australian standard for wind actions: AS1170.2 has incorporated a clause (Cl. 2.5.7) to stipulate the requirement to consider impact by debris in modelling the effects of wind actions. In cyclonic regions in particular it is important to distinguish an "open" building from that of a "closed" building as the magnitude of the design wind forces depend a great deal on this definition. Thus, failure of the building façade by wind borne debris during a severe storm can have serious structural implications.

3. QUASI-STATIC FORCES AND FLEXURAL ACTIONS

The amount of quasi-static force generated by the impact of a dropped object on a simply-supported beam is taken as the sum of the support reactions (ie. 2R) and can be exceeded significantly by that of the contact force because of contributions from the inertial resistance of the target (Figure 1a). The two types of forces is best illustrated by a two-degree-of-freedom (2DOF) system model comprising two spring-connected lumped masses (Figure 1b). Computer algorithms for simulating the response of the 2DOF model can be found in Lam et al. (2010, 2011). The frontal lumped mass represents the impactor whereas the second lumped mass at the rear represents the target. Values of the lumped mass (αm) representing the target and the stiffness of the supporting spring (k_2) at the rear have been derived by the authors in previous publications for beams and plates (Yang et al., 2012a & 2012b). The reaction force is linearly correlated with the displacement demand and the shear forces and bending moments, of the beam (or plate) as a whole. In contrasts, the contact force is associated with localised stresses surrounding the point of contact and is responsible for the risks of localised phenomena such as failure by denting, local crushing or perforation. Modelling the effects of the reaction force is the focus of interests in the rest of this section.



(a) Impact actions on beam



(b) Spring connected lumped masses

Fig. 1 Contact force versus quasi-static actions

The main challenge with the estimation of the reaction force is to do with its sensitivity to changes in the self-weight of the target as a result of impactor-target interactions. This challenge has since been overcome by the author and co-workers with the development of a predictive model based on momentum and energy principles (Ali et al., 2013). If the conditions of no-rebounce of the impactor is assumed, the value of the quasi-static reaction force (2R) and deflection (w) at mid-span of a simply-supported beam is given by equations 1a and 1b respectively.

$$2R = V\sqrt{mk}\beta \qquad (1a) \qquad \Delta = \frac{mV}{\sqrt{mk}}\beta \qquad (1b) \qquad \beta = \sqrt{\frac{1}{1+\alpha}} \qquad (1c)$$

where m = mass of impactor, V = velocity of impact, k = beam stiffness. Equations (1a) – (1c) which are amenable to hand calculations have been validated by systematic physical experimentations along with rigorous computer simulations using program LS-DYNA (Ali et al., 2013). The presented expressions have been simplified as they are based on the assumption of instantaneous momentum transfer, no rebounce of the impactor, linear elastic behaviour of the target support and negligible static deflection by gravity. This set of equations, though appear simple, has profound implications in the risks assessment of damage to fragile items such as glazing panels and ceramic roof tiles. The interesting size effects that are implied by these expressions are presented in Fig. 2 for simply-supported beams and Fig. 3 for simply-supported square plates.

Take the example of a simply-supported beam with a generalised mass which is double the mass of the impactor (i.e. α =2). It is shown in Fig. 2 that as the span length of the beam is increased by a factor of 2 (i.e. increasing α from 2 to 4) the magnitude of the reaction force is reduced to 0.27 times the value associated with the original beam. The bending moment is accordingly reduced to 0.54 times the original value despite having doubled the span length ! The deflection at mid-span of the beam is reduced to 2.16 times the original value. If the same set of expressions are applied for analysing impact scenarios involving smaller projectiles (ie. higher values of α) the reaction force ratio tends to the value of ¼, bending moment ratio tends to the value of ½ and the deflection ratio tends to the value of 2. Applying the same expressions on square plates will see the bending moment ratio tending to the value of ¼ and deflection ratio tending to the value of unity. These figures may appear counter-intuitive when interpreted from restrictive force-based principles. The trends can be articulated readily when the fundamental concepts of increasing mass protection and energy absorption with increasing size (span length) of the target are well understood. It is important to review existing risks models to determine if this important trend has been captured to ensure that resources are effectively deployed to address components which are truly vulnerable.

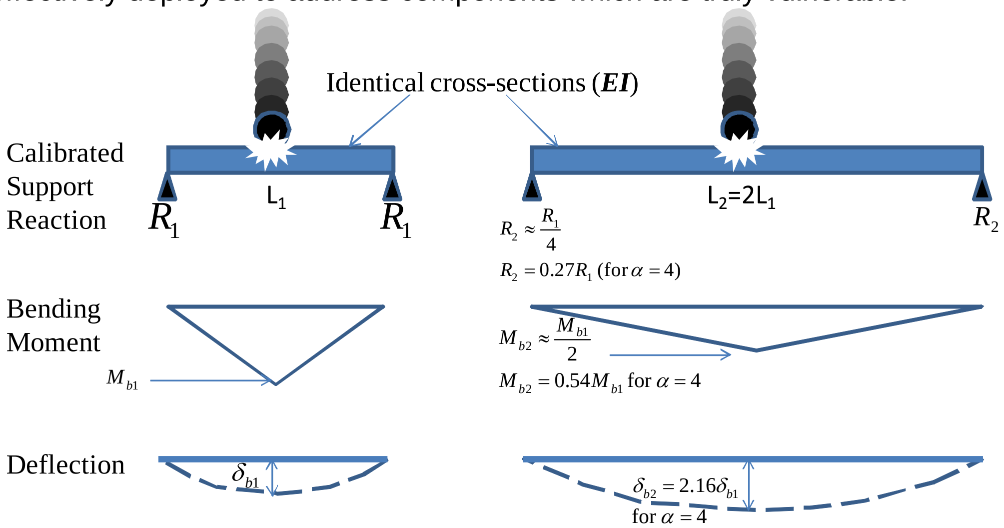


Fig. 2   Scaling relationships for quasi-static impact actions on beams

4. CONTACT FORCES AND DENTING OF METAL PLATES

The main challenge with the estimation of contact forces is difficulties in taking accurate measurements in an impact experiment. Forces are normally measured by load cells in physical experiments. However, placing the load cell behind the target and the rear spring would only measure the reaction force, and not the contact force. Placing the load cell in front of the target for the direct measurement of the contact force can result in damage to the instrument following repetitive testings because of the abrasive nature of impact actions. Any attempt to protect the load cell such as the use of a shield, or cushion, would only compromise the accuracies of the measurements if the actual impact to be modelled is without any protection. Furthermore, readings taken from the load cell in the course of the impact would not automatically provide all the information required for characterising the compressive properties of the impactor.

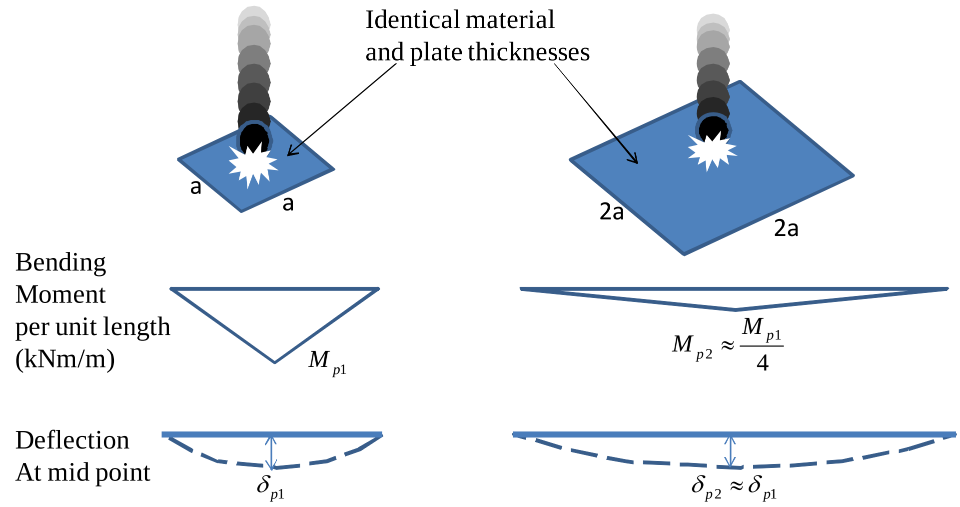
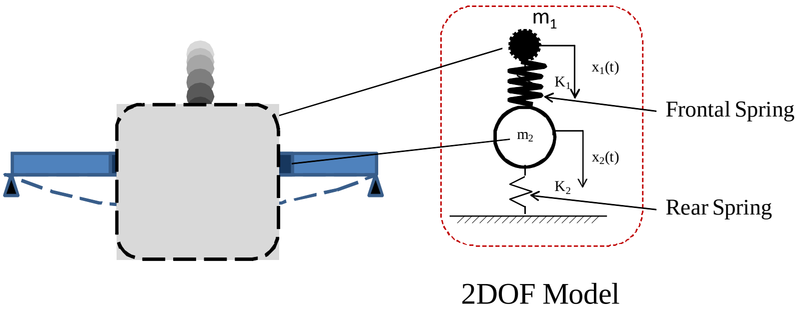
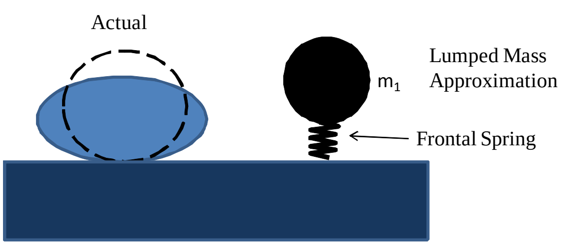


Fig. 3 Scaling relationships for quasi-static impact actions on plates



(a) Spring connected lumped masses representing impactor and beam



(b) Frontal spring representing deformation behaviour of debris impactor

Fig. 4 Two-degree-of-freedom system lumped masses model

The dependency of the force value to the non-linear inelastic compressive stiffness properties of the impactor presents additional challenges with computer simulations when information on such properties are lacking. The deformation behaviour of the impactor can be represented by a carefully calibrated frontal spring in the 2DOF spring-mass system (Figs 4a and 4b). A custom made measuring device (Fig. 5) has been built by the author and co-worker for measuring the contact force generated by an impact and the dynamic compressive stiffness of the impactor. The fundamental operational principle of the measurement device is to incorporate a physical model of a spring mass system within the device in order that the time history of the contact force can be inferred from the directly measured displacement time-histories of the lumped mass. Time-histories of the contact force are then simulated analytically based on assumed compressive properties of the impactor to match with measurements in a two-step calibration procedure. Details of the experimental-calibration procedure are described in Yang et al. (2013).

The apparatus of Fig. 5 has been tried out with tests on sport balls (which have the benefits of reproducing results at a later date). The time-histories of reaction and contact forces measured from a golf ball dropping from a height of 2m are shown in Figs 6a & 6b which reveals an order of magnitude difference between the two forces that are generated from the same impact. The reaction force was observed to be around 40N only and lasted for 30 ms (Fig. 6a) whereas the contact force reached almost 600N and lasted for less than 2 ms (Fig. 6b). Much of the contact force was reacted by the inertia force of the target whereas contributions by the reaction force were very minor. A two-step calibration procedure devised by the author and co-workers enabled the non-linear inelastic stiffness properties of the impactor to be modelled in the form as illustrated in the schematic diagram of Fig. 7a. The two parameters to be calibrated are namely COR (coefficient of restitution) and p. The loading-unloading curves derived specifically for the golf ball using this calibration method is shown in Fig. 7b.

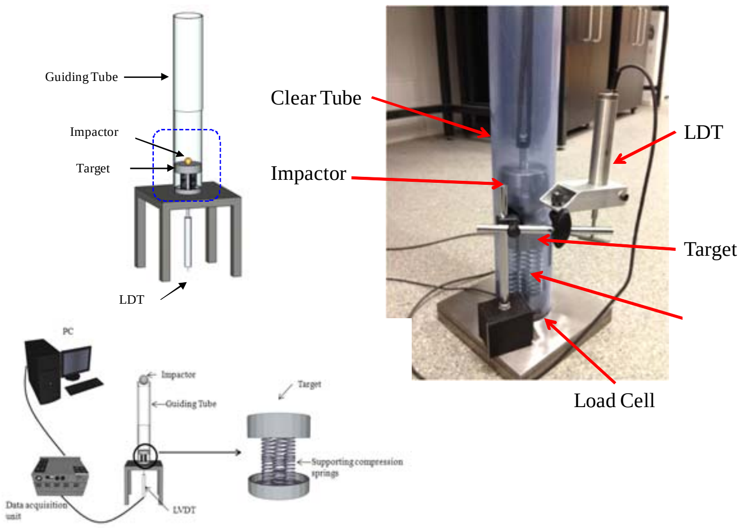
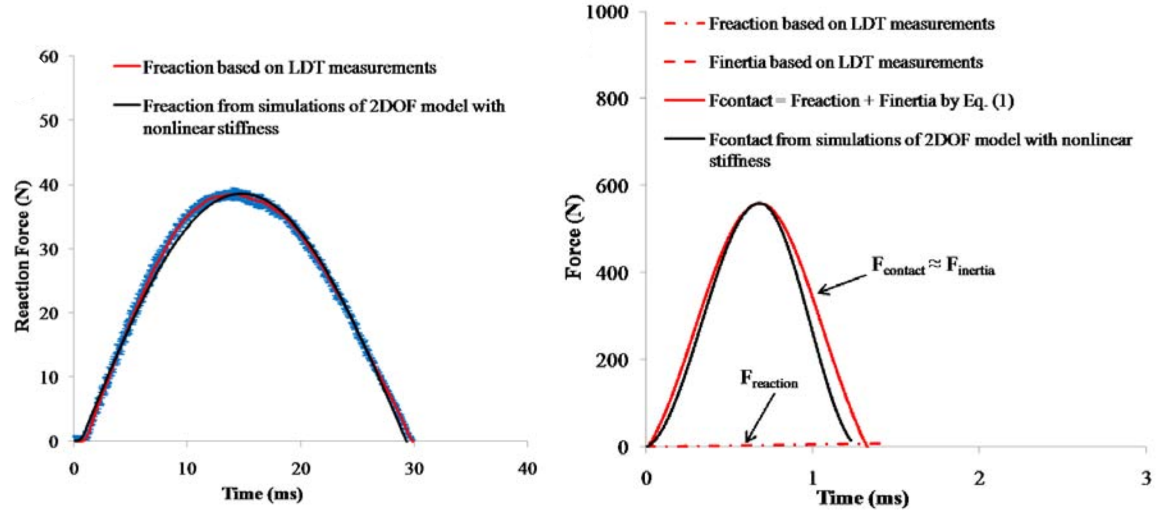
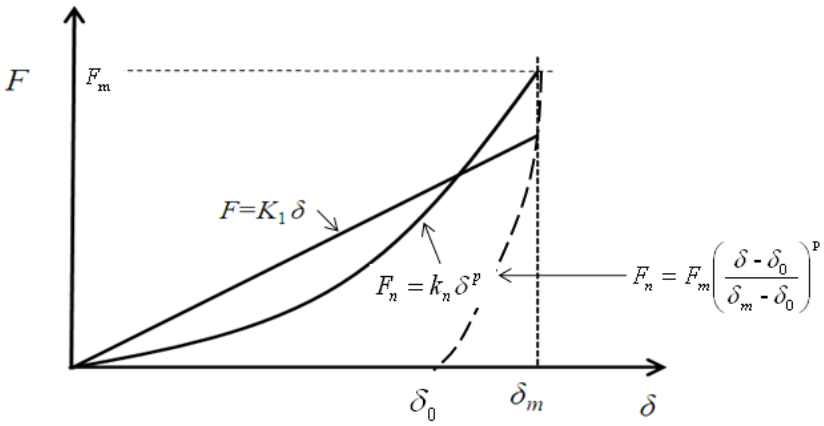


Fig. 5 Custom made tubular device for measuring impact forces

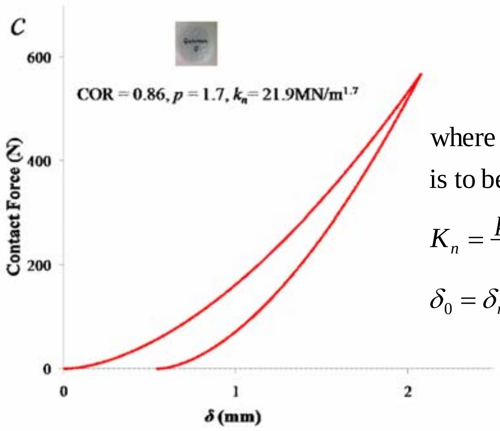


(a) Quasi-Static Force Time-History (b) Contact Force Time-History

Fig. 6 Measured and calibrated impact forces on a golf ball



(a) Non-linear inelastic compressive stiffness model of frontal spring



where the value of p and COR is to be calibrated

$$K_n = \frac{p+1}{2} K_1 \delta_m^{1-P}$$

$$\delta_0 = \delta_m\left(1 - COR^2\right)$$

(b) Calibrated compressive stiffness properties of golf-ball

Fig. 7 Calibrated properties of frontal spring

Once the compressive properties of the impactor is known the amount of contact force generated by a range of impact scenarios involving the same impactor can be estimated reliably using analytical simulations. Experiments conducted to date on impactors using the apparatus of Fig. 5 were of very modest velocity (of up to 6 m/s). An enhanced version of the device featuring a gas gun fitting is being built to extend this methodology to high speed impact scenarios (Fig. 8).

5. CLOSING REMARKS

Storm debris including hailstones accounts for over a third of insured losses from natural disasters in Australia. The most costly components are damage to Terracotta roof tiles and steel sheet roofing by hail and damage to glazing facades and steel cladding by windborne debris. The ingress of water into the building through damaged tiles and the increased wind forces on the building following the failure of the building facades have significant added on effects to the damage.

The reaction and contact forces and their distinctive effects on different types of target were next introduced. The scaling relationships which take into account the size effects of the target were then illustrated with examples. The trends displayed by the illustrations highlighted the important shortcomings of the conventional approach of representing an impact action by an equivalent static load.

Finally, challenges associated with the measurement and prediction of contact forces were identified. A new technique for measuring contact force was then illustrated. The non-linear inelastic compressive stiffness properties of the golf ball as an impactor has been identified by calibration.

This measurement-calibration methodology enables contact forces to be predicted for a range of impact scenarios involving the same impactor. The ultimate objective is to assess the risks of damage to fragile items in order that resources can be deployed effectively to mitigate damage in projected events for the future. Much of these techniques are new as they are unique to the scenarios of projectile and dropped object impact and are distinct to actions by strong wind and blast pressure.

REFERENCES

Ali, M., Sun, J., Lam, NT.K., Zhang, L. & Gad, E.F. (in press), “Simple Hand Calculation Method for Estimating Deflection Generated by the Low Velocity Impact of a Solid Object” Australian Journal of Structural Engineering, Manuscript no. Ref: S13-006, Accepted 25 February, 2013.

Andrews, K. E., & Blong, R. J. (1997). March 1990 Hailstorm Damage in Sydney, Australia. Natural Hazards , 113-125.

Changdon, S. (1977). The scales of hail. Journal of Applied Meteorology, 16, 626-648.

Crompton, R.P. and McAnenev, K.J. (2008). The cost of natural disasters in Australia: the case for disaster risk reduction. The Australian Journal of Emergency Management, 23, 4.

Darling, R. (2012). Damage to infrastructure caused by the impact of hail. Graduate student project report, Infrastructure Engineering, The University of Melbourne. Melbourne, Australia.
EMA (2007). Sydney, NSW: Severe Hailstorm (incl Lightning). Available from Emergency Management Australia Disasters Database.
Lam,.N.T.K., Tsang, H.H. and Gad, E.F. (2010). “Simulations of Response to Low Velocity Impact by Spreadsheet”, International Journal of Structural Stability and Dynamics. 10 (3) : 483-499.
Lam, NT.K., Gad, E.F., Zhang, L. & Yang, Y.(2011). Simple Spreadsheet calculations in support of computational analysis for impact actions. Proceeding of the 2011 World Congress on Advances in Structural Engineering and Mechanics. Seoul, South Korea.
Lin, N., Holmes, J. D. & Letchford, C. W. (2007). Trajectories of Wind-Borne Debris in Horizontal Winds and Applications to Impact Testing. Journal of Structural Engineering, pp. 274-282.
Lin, N., Letchford, C. & Holmes, J. (2005). Investigationof plate-type windborne debris Part 1. Experiment in wind tunnel and full scale. Journal of Wind Engineering and Industrial Aerodynamics, pp. 51-76.
Minor, J. E. (1994). Windborne debris and the building envelope. Journal of Wind Engineering and Industrial Aerodynamics, 53(1), 207-227.
Minor, J. E. (2005). Lessons Learned from Failures of the Building Envelope in Windstorms. Journal of Architectural Engineering , 10, 1076-431.
Schuster, S.S., Blong, R.J., Leigh, R.J., and McAneney, K.J. (2005). Characteristics of the 14 April 1999 Sydney hailstorm based on ground observations, weather radar, insurance data and emergency calls. Natural Hazards and Earth System Sciences, 5, 613-620.
SGIO (2004). Steel roofs guard against hail study. SGIO Insurance. Available at: www.sgio.com.au/pub
Standards Australia. (2011). AS/NZS 1170.2-2011, Sydney: Standrards Australia.
Tachikawa, M. (1988). A method for estimating the distribution range of trajectories of wind-borne missiles. Journal of wind engineering and industrial aerodynamics, pp. 175-184.
TORRO (2006). TORRO Hail intensity scale. Retrieved from the Tornado and Storm Research Organisationwebsite: http://www.torro.org.uk/TORRO/severeweather/hailscale.php
Yang, Y., Lam, N.T.K. & Zhang, L. (2012a), “Evaluation of Simplified Methods of Estimating Beam Responses to Impact”, International Journal of Structural Stability and Dynamics, 12(3) – art no. 1250016.
Yang, Y., Lam, N.T.K. & Zhang, L. (2012b), “ Estimation of Response of Plate Structure Subject to Low Velocity Impact by a Solid Object”, International Journal of Structural Stability and Dynamics, , 12(6) – art no. 1250053.
Yang, Y., Sun, J., Lam, NT.K., Zhang, L. & Gad, E.F. (in press), “Forces Generated by Low Velocity Impact of Common Spherical Objects” International Journal of Impact Engineering, Manuscript no. Ref: IE-D-13-00032, Accepted 4 April, 2013
Yeo, S., Leigh, R., et al. (2000). "The April 1999 Sydney Hailstorm." Australian Journal of Emergency Management, 31, 23-25.