Prediction of plywood deformation under the impact of windborne debris using Taguchi method

O Al-Kubaisi¹, D Mohotti¹ and O Al-Qassag²

¹ The School of Civil Engineering, Faculty of Engineering, The University of Sydney, Darlington, NSW 2006, Australia
² Technical Engineering College-Baghdad, Middle Technical University (MTU), Baghdad, Iraq

Abstract. Windstorms and tornados can cause severe damages to different structure types regardless the materials they have been made of. These damages are caused both by the extreme wind velocity and any flying debris within the wind field. Windborne debris is classified based on shape and aerodynamical properties into three types: compact, rod, and plate-like debris. According to both American and Australian Standards, the performance of any structural element is to be tested under the impact of rod-like debris. Plywood is used globally to create both structural and non-structural elements such as doors and window shutters, and thus, in this study, a numerical simulation of rod-like debris was conducted using LS-DYNA to study the effect of debris impact velocity on the deformation of a plywood plate. In this way, the effect of the plate thickness and modulus of elasticity on the deformation were also investigated. Taguchi Method was adopted to make the simulation more robust and reduce the required computational time and costs. The results showed that as the debris impact velocity increased, both the deformation of the plywood plate at penetration and the residual kinetic energy of the debris increased. However, for the same plate thickness and debris impact velocity, as the modulus of elasticity increased, the deformation of the plate at the point of penetration decreased.

1. Introduction

Extreme wind events such as tornadoes are considered to be natural hazards, but they can cause different levels of damage to many types of structures. Initially, such damage was linked to the extreme wind speeds generated; however, post wind event reports and insurance reviews indicate that a large fraction of such damage is caused by flying debris within the wind field [1]. Surveys have also detected that low-rise residential buildings (residential houses) take the most damage during windstorms, due to their lower budgets during construction, which limits or eliminates professional reviews, engineered design, and quality control during their construction [2]. The failure sequence due to wind for this type of buildings is as follows: (1) Partial failure in the roofing system due to the uplift pressure, allowing wind and moisture to flow into the house; (2) The internal pressure inside the house increases, which may cause the loss of the entire roof and the collapse of the walls; (3) The presence of opened doors and/or windows may rapidly increase the internal pressure and decrease the time required for total failure. These doors and windows may be opened either by the residents of the house, extreme wind gusts, or the impact of windborne debris [2, 3].

Various non-structural objects such as trees and vehicles may become windborne debris in extreme wind events. Moreover, structural parts can be detached from the structure and also become windborne debris due to wind gusts, turbulence, and vertices shading. As the wind gusts exceed 125 km/hr, some structural parts are likely to separate from the structure and become windborne debris with velocities ranging from 53 to 106 km/hr within a short period of time over short distances. The velocity of these
unattached structural parts depends on their conditions of fixing, the wind direction, the wind gusts, the wind velocity, and the aerodynamic properties of the part in question [4-6]. Studying the behaviour of structural envelope elements (windows, doors, and walls) under the impact of windborne debris is very important due to the possibility of debris breaching the structure and increasing the internal pressure, which may endanger lives of the occupants and increase the possibility of total failure of the structure [4-7]. The possibility of a structure being impacted by windborne debris increases when the structure is located downwind to the wind direction because of the domino effect of the debris [4, 7]. Although debris can be formed in various shapes and sizes, all studies on behaviour of structures under debris impact have been limited the classification of debris types made by Wills and Lee [8]. Moreover, the Australian Standards [9] and the American Standards [10, 11] have adopted two types of debris in their testing procedures: the small missile, which refers to compact debris such as sand and gravel particles, and the large missile, which refers to rod-like debris such as parts of the wooden frames of roofs and doors.

Taguchi method is a statistical design of experiment (DOE) method developed by G. Taguchi. It aims to make the design of any product more robust during the research and development phase by optimising factors and reducing costs [12-16]. Taguchi method has been adopted in multiple engineering fields. In Civil Engineering, it has been adopted to optimise the cross-sectional area of ten-bar trusses [17], the mechanical properties of high strength concrete (HS Concrete) with blast furnace slag and silica fume as admixtures [18], the process parameters for Fly Ash bricks [19], and the mix proportions for high strength self-compacted concrete (SCC Concrete) [20]. Furthermore, this method has been used to optimise the design of new frameworks when combined with immune algorithm [21]. This study aims to develop an analytical equation to predict the deformation in plywood plates based on the velocity of debris at impact, the thickness of the plywood plate and the modulus of elasticity of the plywood plate. Such predictions can help in estimating the required plywood plate thickness to offer a cheap protection method for windows during extreme wind events.

2. Finite element modelling
A finite element model was made to simulate the impact of a wooden projectile on a composite plywood plate using LS-DYNA software. In this section, the simulation of both the projectile and the plate is discussed.

2.1. Geometry and elements
A plywood layer with dimensions of 406.4 × 406.4 mm (16 × 16 in) and a thickness of 3.81 mm (0.15 in) was modelled using brick elements, using a size of 3.175 × 3.175 × 3.81 mm (0.125 × 0.125 × 0.15 in) near the impact zone and a size of 6.35 × 6.35 × 3.81 mm (0.25 × 0.25 × 0.15 in) far from the impact zone, as shown in Figure 1. The composite plywood plate was modelled to consist of five plywood layers with a total thickness of 19.05 mm (0.75 in). A large wooden rod with a mass of 6.8 kg (15lb), a cross-section of 50 × 100 mm (2 × 4 in), and a length of 3,658 mm (12 ft) was used as the projectile for this study. However, to reduce the computational time and cost, the chosen projectile was modelled with a small projectile of 38.1 × 88.9 × 38.1 mm (1.5 × 3.5 × 1.5 in) despite maintaining the same inertia as the original projectile. The modelled projectile was then simulated with brick elements of 3.175 × 3.175 × 3.175 mm (0.125 × 0.125 × 0.125 in). Based on the aforementioned element sizes, 34,960 elements were used to simulate the composite plywood plate and a total of 4,032 elements were used to model the projectile.

2.2. Properties of materials
Two different material models were used in this study. For the modelled projectile, material model 20 “MAT_RIGID” was used, with a modified mass density of 5.272 × 10⁻⁵ kg/mm³, a modified modulus of elasticity of 16.719 GPa, and a modified Poisson’s ratio of 0.365, in order to maintain the
same inertia as the original projectile. For the plywood layers, material model 143 “MAT_WOOD_PINE”, which is a transversely isotropic material, was used. The APOT was used in this study to simulate the direction of the plywood layer [22], while the “HOURGLASS” card was used with stiffness hourglass control type 4 and an hourglass coefficient of \( QM = 0.005 \) as recommended by [23].

![Figure 1. Model details (a) Front View (b) Side View](image)

2.3. **Boundary conditions and contact information**
A fixed boundary condition was used for all sides of the plate in order to simulate the full clamping used in experimental work done by Texas Tech University [24]. To simulate the fracture mechanism, an “AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK” card was used between successive plywood layers [22]. To simulate the impact behaviour between the first plywood layer and the wooden projectile, an “ERODING_SURFACE_TO_SURFACE” card was used [22, 24].

2.4. **Model validation**
The validation of the proposed model was done in two stages. The first stage was to compare the calculated results from the model with those obtained from the experimental work conducted by Texas Tech University [24]. Based on the experimental results, the debris impact velocity at which the penetration of the plate occurred was 13.9 m/s which is very close to the penetration velocity obtained from the proposed model (13.8 m/s). The second stage was done by comparing the obtained results with those from other proposed numerical models [22, 24]. This comparison of results is summarised in Figure 2. Based on these comparisons, it was found that the proposed model predicted the penetration debris velocity in an acceptable range when compared to the experimental work, and the relationship between the predicted debris’ residual velocity and its velocity at impact using the proposed model was aligned with those predicted using other proposed models.
3. Dimensional analysis

3.1. Basic relationships

Based on the literature [5, 6, 8-11, 22, 24-27], the total deformation of the target before penetration of the projectile ($\Delta_t$) is a function of the projectile mass ($m_p$) and impact velocity ($V_p$) as well as the target modulus of elasticity ($E_t$) and thickness ($t_t$). Retaining the aerodynamic properties of the projectile as well as the fixity of the target constant for all the tests, this relationship can be written as

$$\Delta_t = f\left(m_p, V_p, E_t, t_t\right)$$  (1)

3.2. Number of independent dimensional groups

Based on Buckingham pi-theorem [28], for any phenomenon governed by number of variables ($n$), the number of independent dimensionless groups required to describe this phenomenon will be ($n - r$); where ($r$) is the number of basic dimensions required to express these variables. Based on the variables in equation (1), the required dimensions to express these variables are mass [$M$], length [$L$], and time [$T$]. Thus, the total number of dimensional groups required is

$$n - r = 5 - 3 = 2$$  (2)

3.3. Dimensional groups

To find these dimensional groups, three variables should be selected as repeating variables. In this study, ($m_p, V_p$ & $t_t$) were initially chosen as the repeating variables. The first dimensional group can thus be found as follows:

$$\pi_1 = \Delta_t \cdot t_t^{a_1} \cdot m_p^{b_1} \cdot V_p^{c_1} = [M]^0[L]^0[T]^0$$  (3)

Solving equation (3), ($b_1 = c_1 = 0$) and ($a_1 = -1$), and by substituting these back into the equation, the first dimensional group becomes

$$\pi_1 = \frac{\Delta_t}{t_t}$$  (4)

Similarly, the second dimensional group ($\pi_2$) is found to be ($E_t \cdot t_t^3 / m_p, V_p^2$) and re-writing equation (1) in terms of the dimensional groups gives

![Figure 2. Comparison between the proposed model and other proposed models [22]](image)
\[ \frac{\Delta t}{t_t} = \phi \left( \frac{E_t t_t^3}{m_p V_p^2} \right) \]  

(5)

where \( \phi \) is the function governing the relationship between \((\pi_1)\) and \((\pi_2)\).

4. Case studies

4.1. Case studies description

After validating the model, several case studies were conducted to study the effect of projectile impact velocity, target thickness, and target modulus of elasticity. In these cases, the projectile impact velocity ranged from 15 m/s to 40 m/s in increments of 5 m/s. To change the target thickness, the number of plywood layers ranged from four to six, giving thicknesses of 15.24 mm, 19.05 mm, and 22.86 mm (0.6 in, 0.75 in, and 0.9 in) respectively. The modulus of elasticity for plywood is directly affected by its moisture content. As a result, the modulus of elasticity for the plywood was selected to be 11.35 GPa, 12.56 GPa, and 15.49 GPa in turn, representing moisture contents of 0.3, 0.2, and 0.1 respectively. To examine all these parameters, the total number of case studies required was 54.

Investigated Cases and Results

In order to reduce computational time and cost, Taguchi Method was adopted to statistically select that fraction of the stated case studies that could adequately represent the full list of case studies. Based on Taguchi orthogonal array [15], the required number of case studies to be investigated was reduced from 54 to 6 case studies as shown in Table 1. By adopting Taguchi method, both computational time and cost were thus reduced by 88.9%. The obtained results from the investigated cases are summarised in Table 2.

Table 1. Investigated case studies according to Taguchi method

| Case Number | \( V_p \) (m/s) | \( t_t \) (mm) | \( E_t \) (GPa) |
|-------------|----------------|--------------|----------------|
| 1           | 15             | 19.05        | 11.35          |
| 2           | 20             | 19.05        | 15.49          |
| 3           | 25             | 15.24        | 12.56          |
| 4           | 30             | 22.86        | 15.49          |
| 5           | 35             | 22.86        | 11.35          |
| 6           | 40             | 15.24        | 12.56          |

Table 2. Results obtained from the investigated cases

| Case Number | Projectile Residual Velocity Ratio \((V_{RP})\) | \( \Delta t \) (mm) |
|-------------|-----------------------------------------------|--------------------|
| 1           | 0.216                                         | 8.74               |
| 2           | 0.526                                         | 11.47              |
| 3           | 0.754                                         | 11.63              |
| 4           | 0.657                                         | 15.52              |
| 5           | 0.695                                         | 15.75              |
| 6           | 0.861                                         | 28.9               |

4.2. Regression analysis

A multi-linear regression analysis was adopted to predict the full list of case studies based on the results obtained from the investigated case studies. The following equation was used to predict \((\Delta t)\) and \((V_{RP})\) and the parameters \((A_0 - A_3)\) are shown in Table 3:

\[ Y = A_0 + A_1 \times V_p + A_2 \times t_t + A_3 \times E_t \]  

(6)
Table 3. Parameters obtained from Taguchi method to predict $\Delta_t$ & $V_{Rp}$

| Parameters | $\Delta_t$ | $V_{Rp}$ |
|------------|------------|----------|
| $A_0$      | 3.011      | 0.021    |
| $A_1$      | 0.775      | 0.021    |
| $A_2$      | -0.135     | -0.021   |
| $A_3$      | -0.406     | 0.031    |

5. Results

Based on equation (6) and table 3, both the residual velocity of the debris ($V_{Rp}$) and the total deformation of the target ($\Delta_t$) can be found for the entire set of case studies. The effect of the target thickness and the target modulus of elasticity with different debris impact velocities on the residual velocity of the debris are shown in Figure 3, while their effects on the total deformation of the target are shown in Figure 4.

![Debris Residual Velocity](image1)

(a) Debris residual velocity (a) Effect of thickness (b) Effect of modulus of elasticity

![Target Deformation](image2)

(a) Target total deformation (a) Effect of thickness (b) Effect of modulus of elasticity

Based on these results, the function $\phi$ in ‘equation (5)’ can be found by drawing both ($\pi_1$) and ($\pi_2$) as shown in Figure 5. Equation (5) can then be re-written as

$$\frac{\Delta_t}{t_t} = 4.3495 \left( \frac{E_t}{m_p} \frac{v_p^3}{t_t^2} \right)^{0.582}$$

(7)
6. Conclusions
Based on the results, the following conclusions can be drawn:

1. The adoption of Taguchi method saved 88.9% in terms of both computational cost and time to obtain the results.
2. As the impact velocity of the debris increases, both the debris residual velocity and the target total deformation increase.
3. As the thickness of the target increases, both the debris residual velocity and the target total deformation decrease.
4. As the modulus of elasticity of the target increases, the target total deformation decreases, while the debris residual velocity increases.
5. The equation developed based on the Buckingham pi-theorem [28], equation (7), can predict the total deformation of a plywood target required for large wooden debris to penetrate it with \( R^2 = 0.9377 \).

7. References
1. Minor, J.E., *Lessons learned from failures of the building envelope in windstorms*. Journal of Architectural Engineering, 2005. 11(1): p. 10-13.
2. Cochran, L. *Wind issues in the design of buildings*. 2012. American Society of Civil Engineers.
3. Habte, F., A.G. Chowdhury, and I. Zisis, *Effect of wind-induced internal pressure on local frame forces of low-rise buildings*. Engineering Structures, 2017. 143: p. 455-468.
4. Kaye, N.B., *Wind-Borne Debris Hazards*. 2018: American Society of Civil Engineers.
5. Perera, S., *Modelling impact actions of flying and falling objects*. PhD Dissertation, University of Melbourne. 2017.
6. Letchford, C., N. Lin, and J. Holmes, *Windborne Debris in Horizontal Winds and Applications to Impact Testing*, in Advanced Structural Wind Engineering. 2013, Springer. p. 197-215.
7. Dao, T.N., J.W. van de Lindt, D.O. Prevatt, and R. Gupta, *Probabilistic procedure for wood-frame roof sheathing panel debris impact to windows in hurricanes*. Engineering Structures, 2012. 35: p. 178-187.
8. Wills, J.A.B., B.E. Lee, and T.A. Wyatt, *A model of wind-borne debris damage*. Journal of Wind Engineering and Industrial Aerodynamics, 2002. 90(4-5): p. 555-565.
9. Standards Australia/New Zealand, *Structural design actions, Part 2: Wind actions*, AS/NZS 1170.2:2011(R2016), 2011.
10. ASTM E1886-13a, *Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials*. ASTM International, West Conshohocken, PA, 2013.
11. ASTM E1996-17, Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Windborne Debris in Hurricane. ASTM International, West Conshohocken, PA, 2017.
12. Wood, K.L. and E.K. Antonsson, Computations with Imprecise Parameters in Engineering Design - Background and Theory. Journal of Mechanisms Transmissions and Automation in Design-Transactions of the Asme, 1989. 111(4): p. 616-625.
13. Unal, R. and E.B. Dean, Taguchi approach to design optimization for quality and cost: an overview, in the 1991 Annual Conference of the International Society of Parametric Analysts. 1990.
14. Roy, R.K., Design of experiments using the Taguchi approach: 16 steps to product and process improvement. 2001: John Wiley & Sons.
15. Roy, R.K., A primer on the Taguchi method. 2nd Ed. ed. 2010: Society of Manufacturing Engineers.
16. Atil, H. and Y. Unver, A different approach of experimental design: Taguchi method. Pakistan Journal of Biological Sciences, 2000. 3(9): p. 1538-1540.
17. Lee, K.H., I.S. Eom, G.J. Park, and W.I. Lee, Robust design for unconstrained optimization problems using the Taguchi method. Aiaa Journal, 1996. 34(5): p. 1059-1063.
18. Turkmen, I., R. Gul, C. Celik, and R. Demirboga, Determination by the Taguchi method of optimum conditions for mechanical properties of high strength concrete with admixtures of silica fume and blast furnace slag. Civil Engineering and Environmental Systems, 2003. 20(2): p. 105-118.
19. Chaulia, P.K. and R. Das, Process Parameter Optimization for Fly Ash Brick by Taguchi Method. Materials Research-Ibero-American Journal of Materials, 2008. 11(2): p. 159-164.
20. Ozbay, E., A. Oztas, A. Baykasoglu, and H. Ozbebek, Investigating mix proportions of high strength self compacting concrete by using Taguchi method. Construction and Building Materials, 2009. 23(2): p. 694-702.
21. Yildiz, A.R., A new design optimization framework based on immune algorithm and Taguchi's method. Computers in Industry, 2009. 60(8): p. 613-620.
22. Otkur, M., Impact modeling and failure modes of composite plywood, in Mechanical Engineering 2010, Texas Tech University. p. 124.
23. Murray, Y.D., Manual for LS-DYNA wood material model 143. 2007, United States. Federal Highway Administration.
24. McPeak, B., A transdisciplinary systems approach for defining Tornado characteristics and debris impact analysis. 2009, Dissertation, Texas Tech University.
25. Boughton, G.N., Tropical Cyclone Debbie: Damage to Buildings in the Whitsunday Region. Technical report / Cyclone Testing Station, College of Science and Engineering, James Cook University; no. 63. 2017, Townsville, Queensland: Cyclone Testing Station, James Cook University.
26. Song, F. and J. Ou, Windborne Debris Damage Prediction Analysis, in Computational Structural Engineering. 2009, Springer. p. 497-503.
27. Song, F. and J. Ou, Windborne debris damage prediction analysis. Frontiers of Architecture and Civil Engineering in China, 2010. 4(3): p. 326-330.
28. Shames, I.H., Mechanics of Fluids. 4th ed. 2003: McGraw-Hill.