Engineering Failure Analysis 94 (2018) 412–437

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Review

Applications of finite element modelling in failure analysis of laminated glass composites: A review

Meenu Teotia*, R.K. Soni

Department of Chemistry, Chaudhary Charan Singh University, Meerut, UP 250004, India

ARTICLE INFO

Keywords:
Laminated glass
Modelling
Simulation
CLPT
FSDT
Zigzag
FEM
Automobile windshields
Failure analysis
Blast loading

ABSTRACT

The subject of the paper is modelling of complex damage behaviour of laminated glass, which is a sandwiched polymer composite. Last 20 years have witnessed extensive growth in computational modelling of complex nonlinear behaviour of laminated glass panels with viscoelastic interlayers. Present review article is an attempt to highlight applications of finite element approach in failure analysis of laminated glasses. Evolution of modelling theories such as equivalent single layer theories, layerwise theories and zig-zag models have been presented to insight the fundamental concepts used in modelling. Finite element techniques such as erosion, cohesive zone and extended finite element methods available in FE packages are briefly reviewed alongwith material models for glass and interlayer. The systematic growth in FE models in numerical simulation of human head impact on windshields and blast loading is specifically presented. Finite element models have been proposed as useful guides to engineers for fabrication of laminated glasses with more realistic data to be used in real world situations without going for expensive and time consuming experimental set ups. Overall 223 research articles have been included exhibiting the research performed in context of laminated glass.

1. Introduction

Damage prediction of polymer composites involves determination of impact forces & induced stresses and application of suitable failure criterion for initial failures. Upto 1991, a large amount of experimental data was published and several important features of impact damage were identified. Polymer composites have been reviewed by various authors detailing their damage behaviour and modelling of damage characteristics. Abrate [1] organized all the experimental findings and presented a very comprehensive review of impact of laminated composites. Several types of simple models such as spring mass models, energy balance models were accounted for the behavior of structure, impactors and the local deformation of contact force. In further attempt, Abrate [2] organized newer developments and focused on low velocity impact damage, the damage predictions and evaluation and prediction of residual properties of damaged laminates. The author compared and analyzed various mathematical models and two & three dimensional elasticity models. Impact damage, how it develops and what factors influence impact resistance were highlighted and a detailed description of experimental techniques, failure modes, effect of material properties, effect of projectile characteristics, effect of layup and preload and effect of environmental conditions were presented. Liu and Zheng [3] reviewed damage modelling and finite element analysis for carbon fiber reinforced polymer matrix composite laminates. Finite element implementation of progressive failure analysis in terms of the mechanical response for the variable stiffness composite laminates arising from the continuous failure was presented. The nature and mechanics of damage in brittle layer structures with soft interlayers under concentrated loads was

* Corresponding author.
E-mail address: teotiameenu@gmail.com (M. Teotia).

https://doi.org/10.1016/j.engfailanal.2018.08.016
Received 17 April 2018; Received in revised form 13 July 2018; Accepted 12 August 2018
Available online 16 August 2018
1350-6307/

reviewed extensively by Lawn in the year 2002 [4]. The results of contact studies on monolayer, bilayer, trilayer, and multilayer test specimens that enable simple elucidation of fundamental damage mechanics and yet simulate essential function in a wide range of practical structures were discussed in detail. Composite laminates involve a wide range of materials, underlayers and as well as fibres used in their preparation and hence the prediction of their damage characteristics requires detailed knowledge of their mechanical properties, orientation modes and corresponding materials characterization data. Most of the reported reviews detail damage characteristics and impact behaviour of fibre reinforced composite laminates. The discussion of variety of composite laminates is beyond the scope of our review. After extensive literature survey, we observed that no review is available on damage modelling of laminated glass panels revealing the methods used for predictions of their damage characteristics under different types of impact loadings.

Laminated glasses are sandwiched polymer composites, formed with brittle outerlayers and soft or compliant supporting interlayers which shield from potentially deleterious external forces. They have been used extensively in architectural and structural applications [5–7], automotive windshields [8,9], safety and security endangered buildings [10], defence [11], railways, aerospace applications [12], encapsulant materials for solar cell modules [13] to name a few. Because of their high strength and high modulus, these glasses can be tailored for desired specific applications. The types of glass used in construction industry are annealed, heat strengthened, toughened (fully tempered) and laminated. Annealed glass is cooled gradually from a high temperature to minimize residual stresses during manufacturing process. However, heat strengthened and toughened glass undergo controlled heating and cooling process to have 24-69 N/mm^2 and over 69 N/mm^2 residual compressive surface stresses, later involves high cooling rate. Laminated glasses are commonly used as windshields and in building facades to resist high impact loads. The strength, breakage performance and post failure behaviour of laminated glass depends upon glass type, thickness, dimensions and interlayer geometric and material properties. The use of annealed glass and heat strengthened glass is suggested for fabrication of laminated panels [14]. Building industry is devoting full consideration to the performance of glazing materials in the event of explosive blasts and looks forward to materials and glazing systems that can perform much better under such extreme loadings. Among all the type of safety glasses, laminated glass is the preferred choice as it can resist high pressures and avoids the formation of large shards when glass breaks. Laminated glass offers multifunctional benefits owing to its versatility and being used in a variety of innovative applications. It possess huge architectural capabilities and physical barrier properties have contributed to make it an excellent safety glazing providing solution to increasing demand in view of environmental threats and security. Remnikov et al., [15] experimentally investigated the load deformation response of these blast resistant façade glazing solutions adequately replicating the real world situations. The authors concluded that laminated glass exhibits superior prefracture performance and higher peak resistance and also favourable post fracture behaviour. Impact damage of laminated materials is a matter of great concern as it affects the mechanical properties severely. Foraboschi [16] presented a criterion for fail safe design of glass plates loaded transversally. Three conditions have been putforth; 1) any piece of glass that has a certain amount of redundancy, glass has two types of cracks, initial (during manufacturing process) and contact induced cracks (due to live loads), the former is substantial however later is marginal and hence can be neglected while assessing the load carrying capacity, 2) in the event of breaking no sharp shard should be fall to avoid injury and 3) the glass must have postfracture load carrying capacity, means if one glass fails the structure must remain standing until total failure. Laminated glass is the only product able to satisfy second and third fail safe condition. Specific glass types are recommended to obtain a failsafe laminated glass system. A sacrificial ply (ply which is allowed to fracture in service due to live load) has to be made of toughened glass as it can tolerate high local tension stress and also glass disintegrates into small pieces when it breaks. Laminated glasses can be made by using different type of glasses and no manufacturing restrictions are involved. These are used as primary (floor & roofs), secondary (staircases, overhead glazing supported by primary structures) or as non-bearing elements (facades & partitions). Simulation of damage behaviour is not only important to structural glasses (load bearing) but is also important for non structural (architectural/non-load bearing) as the later such as windows, glass façade panels, overhead glazings, skylights offer structural defense to the building envelope in the event of naturally occurring phenomena such as earthquakes, windstorms, snowstorms alongwith live loads.

Compression, bending, shear and residual strength of impact damaged specimens can be determined experimentally but the assessment of all possible combinations of laminate construction experimentally would be expensive and time consuming. Despite of profound advantages and applications of laminated glasses, still their use is limited because of the problems in strength calculations at the stage of their design for a particular application. Hence, modelling of damage behaviour of laminated glasses has become an essential pre requisite to stimulate an effective developmental process in context of their expanding use in aerospace and other important industries. This provides effective working guidelines for predetermining optimum material combinations in applications for desirable end use. Impact behaviour of laminated glasses can be modelled analytically or numerically. Analytical methods gives exact solutions however numerical simulations give approximate solutions. The former may be useful for numerical solutions of the formulated problem and later may be helpful in finding out solutions to differential equations that cannot be solved exactly. A lot of research has been devoted to analytical modelling of glass using theoretical approaches such as classical plate theory or Von Karman's large deflection theory. Foraboschi [17] put great efforts in developing analytical models for three layered plates and reported analytical models to understand mechanical behaviour of three layered plates using a system of three exact and explicit equations subjected to lateral static loading using Kirchoff's-Love plate assumptions. The models provides exact results and can be used to validate numerical models and offers scientific understanding of deformation process and mechanical failure of TLPs and their underlying physical mechanisms [18]. The approximate results obtained through FE models suffer inaccuracy due to high glass to interlayer stiffness ratio. Hence validation of FE predictions either experimentally or analytically is a prominent requisite in order to obtain accurate predictions. In continuation of this work, the author proposed an easy to use analytical closed form solution for three layered plates which can be used to calibrate FE models in a straightforward manner [19]. Previous models were suitable to simulate