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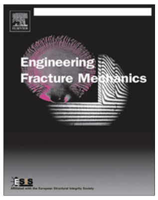

Review

Laminated plate theories and fracture of laminated glass plate – A review

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ABSTRACT

The designed fracture of laminated glass (LG) makes it useful for architectural, glazing, automotive safety, photovoltaic, ultraviolet ray protection, and decorative applications. The present review is divided into three sections: the first section includes a description and classification of the laminated plate (LP) theories that are used to explain fracture of LG plate, second section comprises explanation of fracture of LG samples during three-point bending, ring on ring and ball drop impact testing using linear elastic finite element (FE) model and the last section includes numerical simulations techniques used for explaining the impact fracture of LG. The outcome of the review highlights the requirement of quantitative work on crack propagation prediction during LG fracture and critical evaluation of the numerical algorithms available for modeling the glass-ply cracking and principal damage pattern in LG. This review paper is meant for the faster comprehensive understanding of this research area.

Contents

1. Introduction

LG comprises of two layers of glass and one or more layers of the polymer film (inter-layer) that is sandwiched in-between using heat and pressure. Glass is a non-crystalline material that exhibits a glass transition (reversible change from a tough and brittle state from a molten/ rubber-like state) and disordered atomic structure. Glasses are hard, good electrical

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and thermal insulators, brittle, mostly optically transparent, chemically inert, materials without exact melting point, high compressive strength isotropic materials and mostly composed of O, Si, Fe, Al, Ca, Na, K, and Mg. Glass is not a single compound thus, the chemical formula of glass is expressed as combination of silica dioxides, alkali oxides, and metal oxides. The chemical formula of glass can be expressed as aX_2O bYO $6SiO_2$ where, a, b are number of molecules; X is an atom of an alkali metal i.e. Na, K etc, Y is an atom of a bivalent metal i.e. Ca, Pb etc, for example, Soda-lime Glass - Na_2O CaO $6SiO_2$ Potash-lead Glass - K_2O PbO $6SiO_2$ and so on. The glasses can be made of the variety of materials, metallic alloys, ionic melts, aqueous solutions, molecular liquids, and polymers (acrylic glass, polycarbonate, polyethylene terephthalate). The most common glass is soda-lime-silica glass having sand (contains silica), soda ash and limestone, and also a smaller amount of various additives. Annealed glass is the fundamental flat glass product that is the first outcome of the float process. Annealed glass is also formed by heating the constituents' up to fusion and then cooling the mixture to a rigid state in a prescribed atmosphere. Annealing causes the internal stresses to relieve slowly, However, An annealed glass tends to break into big jagged shard thus it can't be used in heavy traffic area. An annealed glass is also an initial material for producing superior products through further dispensation such as toughening, laminating, and coating. Tempered glasses/ toughened glasses are produced by controlled chemical or thermal treatments that increas the strength of glass and modify the fracture pattern (tempered glass breaks into small, square fragments). Surface coatings are applied to glass for modified appearance, low maintenance, improved transmission, absorption properties, scratch and corrosion resistance. Heat-strengthened glass is produced by heat treating to stimulate surface compression that result-in glass with the intermediate strength between tempered and annealed glass. When broken, it breaks off into sharp pieces that are squarer and smaller than that of annealed glass but less square and bigger than that of tempered glass [1–5].

The effect of the interlayer material on the stiffness, impact strength, fracture pattern, and the load-bearing capacity of LG plate is well known. Most commonly polyvinyl butyral films (PVB) and Ethylene Vinyl Acetate (Cross-Linked EVA) are utilized as inter-layer material. However, in addition to PVB and EVA, Ionoplast Polymers, Cast in Place (CIP) liquid resin and Thermoplastic polyurethane (TPU) are also used as inter-layers and sanitary glasses are also becoming popular. Inter-layer improves mechanical properties like impact strength, fracture toughness and failure mode of LG [1]. As the area of impact increases, there is a possibility of increment of the impact resistance. The fracture of LG is designed so as to the Inter-layer keeps together the broken pieces that can possibly cause dangerous incidents or accidents. The LG dampens the energy of impact and improves the brittle fracture behavior when compared with the monolithic glass. This functionality forces designers to use LG wherever there may be an injury risk due to glass fracture. The LG has inter-layers considering their end uses i.e. automotive industry, architectural industry, photo-voltaic, decorative, specialty market and fire resistance.

A good number of theoretical studies [6–13], experimental studies [14–22,42–45,48], numerical studies [15,23–48], numerical studies using LS DYNA and ABAQUS [23–31,40,41], and discrete element (DE)/finite element (FE) based studies are reported to analyze impact failure of LG. The bending behavior of LG is also discussed widely [49–69]. The thermal breakage of LG during fire condition is discussed in [70]; it was found that LG prevents new vent formation during the fire. The time-temperature dependent behavior of PVB and its application to LG is also discussed recently [71]. The present work is focused on reviewing the LP theories and numerical algorithms used to model the impact fracture of LG.

2. Laminated plate theories

LG plates are widely used in automotive, structural, architectural, glazing, photo-voltaic decorative, defense and other applications. LG plates are often subjected to impact loading (windshields, structural applications) which can cause serious accidents. The numerical simulations are the competent way to facilitate lesser design costs, design time, and safer structures. Thus, the numerical methods are used extensively for estimating the design parameters in LG structures.

Laminated composite plate theories include First-order shear deformation theory (FSDT), Higher-order shear deformation theory (HSDT), Classical Lamination Theory (CLT), Zigzag Theory (ZZT), Layer-wise Lamination Theory (LLT), and 3D Elasticity Theory. The theories used for sandwich and LPs are reviewed by Altenbach [72]. Theories that are applicable to shear deformation modeling of hybrid LP are reviewed by Noor and Burton [73,74]. The layer-wise LP theories are discussed by Reddy and Robbins [75]. Liu and Li [76] evaluated the LP theories based on the displacement assumptions and also develop a technique [77] for convincing the prerequisite of completeness by including all the terms up-to third order in the assumed displacement field for the LP theory. The theories including the dynamic response of LPs were discussed by Sun and Whitney [78]. The prime focus of their study was to evaluate the consequence of the diverse shear deformation on the plate thickness. A generalized shear deformation (two-dimensional) theory for LPs was developed by Reddy [79]. The progress of the FE analysis for LPs from 1990 to 2008 was reviewed by Zhang and Yang [80]. Khandan et al. [81] have also reviewed different methods used for modeling of the LPs with special emphasis on the normal stresses and the transverse shear. The FE theories developed for anisotropic, multi-layered, shell structures, and the composite plate was reviewed by Carrera [82]. The progress of displacement based theories for LPs with an insight on efficiency and accuracy was discussed by Wanji and Zhen [83]. The inter-laminar stresses and displacements were analyzed by Matsunaga [84] using a global higher-order theory of cross-ply LPs. A higher order shear deformable LP theory was developed using an inverse method in 3D elasticity bending solutions [85]. The theory was utilized for the solving for the bending related problems of LPs and also for the stress analysis effectively (results were compared with existing shear deformation theories) [86,87].