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Numerical simulation of the shock spalling failure of bonded fibre–epoxy strengthening systems for metallic structures

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ABSTRACT

Fibre–epoxy strengthening systems have been identified as a suitable approach for metallic structures subjected to explosive loads, to increase the structural performance of existing structures and/or create high performance hybrid structures. However, experimental studies have shown that when subjected to the blast pressures resulting from the detonation of explosives, the epoxy bond material may fail by shock spalling, substantially reducing the performance of the strengthening system. Shock spall failure involves tension fracturing of the epoxy material, resulting from tension stress waves generated as the shock wave moves through the composite structure, creating wave reflections and interactions at the constituent boundaries. The experiments investigated a limited range of blast environments due to the limitations of laboratory testing. The present study validates numerical models of the experimentally observed shock spalling failures, and then extends the models to investigate the effect of a broad range of blast environments, metal geometric and material properties, epoxy bond material properties and fibre layouts on the shock spalling failure of the epoxy bond. The numerical results are used to provide generalised considerations for the design of bonded fibre–epoxy strengthening systems for metallic structures, in the form of iso-damage curves for the spall damage and spall failure of such systems in a variety of practical blast environments.

1. Introduction

Fibre–epoxy strengthening systems have long been applied to concrete structures to repair and strengthen structural systems in a wide variety of applications. Over recent decades, the application of fibre–epoxy strengthening systems to metallic structures has been attracting increasing attention for a wide variety of quasi-static applications. Some advantages of bonded fibre–epoxy systems over conventional approaches of adding extra metal (by bolting or welding) are typically identified as; higher strength and stiffness, reduced mass, elimination of welding, corrosion resistance, etc. [1–3].

More recently, fibre–epoxy strengthening has been identified as a suitable approach for metallic structures subjected to dynamic impact loadings, to increase the structural performance of existing structures and/or create high performance hybrid structures. For example, a number of studies have investigated fibre-composite strengthening of metal hollow tubular sections under axial crushing [4–6], and their application to vehicle structures in collisions [7,8]. The metal–fibre bond has been shown to be particularly important in such applications [9], and conventional bonding techniques have been shown to be suitable for impact conditions [10,11]. Some investigations have also specifically studied the metal–fibre bond under low speed dynamic conditions, and have found them suitable for such applications [12].

Similarly, fibre–epoxy strengthening systems and metal–fibre hybrid systems have recently been identified as a suitable approach for metallic structures subjected to blast loadings, including in the infrastructure, offshore and security industries. For example, Nwankwo et al [13] presented analytical and numerical studies of the use of bonded carbon fibre composite patches to strengthen stainless steel blast walls on offshore structures for enhanced blast resistance. The fibre–epoxy strengthening system was assumed to be perfectly bonded to the blast wall, and consequently substantial improvements in the blast resistance of the walls were demonstrated. Several studies have investigated the blast resistance of metal–fibre hybrid structural systems manufactured by bonding alternate thin plates of aluminium and glass fibres (termed metal–fibre-laminates) [14–20], and sandwich systems composed of different materials [21–27]. Such hybrid structures have demonstrated substantial resistance to explosive loads.

However, experimental studies of metal structures strengthened with bonded carbon fibres have noted the susceptibility of the bond

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to failure by 'shock spalling' [28]. In these experiments layers of carbon fibres were bonded to the underside of aluminium beams (away from the blast), by applying successive layers of epoxy bond then fibres (with up to five layers of fibres). The members were then subjected to blast loads from explosives. Shock spalling involves tensile fracturing of the epoxy bond material, and occurs when the tension stresses exceed the tension resistance of the bond material. Tension stresses develop as a result of shock wave reflections and interactions. At the metal-bond interface and each successive interface of bond and fibre layers, some of the incidence shock wave is reflected. The reflected waves interact with the incident wave and other wave reflections, and tension stresses are generated. Since the tensile strength of the bond material used in the experiments was substantially lower than the compressive strength, the bond was susceptible to shock spalling, and in many cases this occurred to such an extent that the fibre layers completely separated away from the metal and were thus incapable of carrying load. Experimental studies of blast loaded metal–fibre-laminates have also shown substantial debonding failures, where individual fibre and metal layers separated from one another [14–16]. Back face debonding was shown to generally increase with increasing explosive mass, and was postulated to be a spalling mechanism resulting from the generation of tensile waves as a result of shock wave reflections [14–16].

In the experiments on fibre-composite strengthening of metal beams [28], the explosive was placed in close proximity to the member. This allowed a relatively small explosive charge to be used, enabling the experiments to be performed in a laboratory and hence many specimens could be tested under controlled conditions (58 explosive tests). A blast load magnitude above which the bond typically failed by shock spalling was identified. However, while the transverse displacement response of metal beams to impulsive load is well known to be largely independent of the exact dimensions of the pressure pulse, depending only on the magnitude of the impulse [29], this is not the case for the shock spalling of the bond. This is due to the fact that shock spalling results from the amplitude of the peak internal tension stress wave, the magnitude of which is directly related to the peak blast shock pressure not the magnitude of total impulse. Different combinations of explosive mass and stand-off distance (distance between the explosive and the surface of the member) can result in pressure peaks and load durations that differ by several orders of magnitude for the same impulse magnitude, however in the experiments only the explosive mass was varied while the stand-off remained constant. Thus a more generalised relationship between the epoxy bond spall failure and the explosive mass, stand-off and peak pressure could not be established in that study. The present study uses numerical modelling to investigate the effect of a broad range of blast environments, metal geometric and material properties, epoxy bond material properties and fibre layouts on the shock spalling failure of the epoxy bond, and provides generalised considerations for the design of bonded fibre–epoxy strengthening systems for metallic structures.

The specific aims of the present paper are to: validate a numerical model of the shock spalling failure of the epoxy bond in the experiments of fibre–epoxy strengthened metal beams under transverse blast load [28]; extend the numerical model to consider a wide range of blast environments generated by varying the explosive mass and stand-off, and a variety of metal and epoxy member dimensions, material properties and fibre layouts; and provide design guidance in the form of iso-damage curves for the spall damage and spall failure of such systems in a variety of practical blast environments.

2. Experiments on aluminium beams strengthened with bonded carbon fibres under blast load

The experiments on aluminium beams strengthened with bonded carbon fibres and subjected to transverse blast load are reported in [28], and are briefly summarised herein. The experimental program involved 12 quasi-static and 58 impulsive tests of aluminium beams strengthened with carbon fibres. Three different beam depths (6 mm, 10 mm and 12 mm) and three different carbon fibre layouts (1, 3 and 5 layers) were investigated. The specimens were manufactured by hand layup whereby a layer of epoxy was applied to the beam surface, then a sheet of carbon fibres was laid, then additional layers of epoxy and fibres were laid according to the desired number of carbon fibre layers. The beams were 500 mm in length, with 100 mm at each end clamped into the test frame, resulting in a beam free span of 300 mm, as shown in Fig. 1. The quasi-static tests were performed as clamped beams under a point load at mid-span, and the impulsive tests were performed as clamped beams under a uniformly distributed impulse resulting from the application of explosives (longitudinal strips of PETN located 13 mm above the beam surface). The explosive strips were detonated at the beam mid-span and the impulsive load was measured with a ballistic pendulum. In both cases the carbon fibres were applied to the flexural tension zone of the beam, that is the side of the beam opposite to the side on which the load was applied. The carbon fibre strips had a length of 300 mm such that they were only bonded to the beam free span and did not extend into the clamped supports. Thus the strain in the carbon fibres developed directly from the epoxy bond between the metal and the fibre, rather than from tension membrane action resulting from

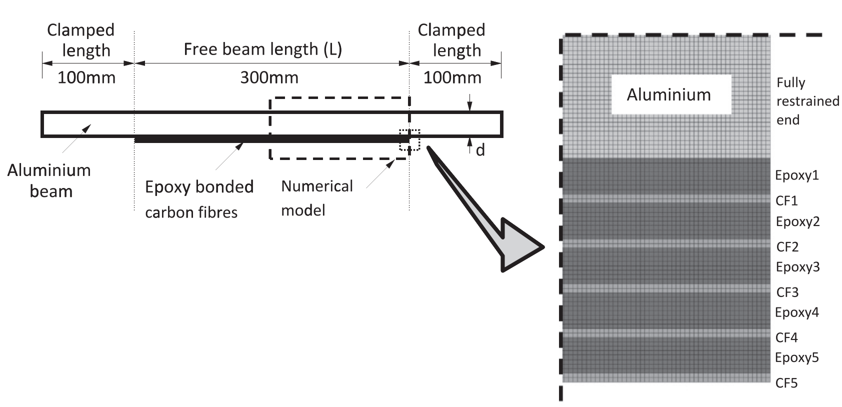

Fig. 1. Aluminium beam test specimens with bonded carbon fibres [28] and FE model of the same with a close-up view of the mesh for the beams with five layers of carbon fibres. Each epoxy and CF layer is 0.8 mm and 0.2 mm thick, respectively. CF = carbon fibre layer.