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FROM DYNAMIC DEBONDING FAILURE TO INTERFACE CHARACTERIZATION IN SANDWICH SYSTEMS

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1. INTRODUCTION

Sandwich structures are layered structural systems that are composed of distinct material layers that considerably differ in thickness, stiffness, strength, thermomechanical properties, density, and role in the structural assembly. Due to their layered nature, such sandwich systems include interfaces that combine the physical layers together. Examples of such interfaces are found al the link between the core and the face sheets in classical sandwich applications but also between the adhesive layers and the adherents in adhesively bonded structural forms.

The functioning of all such forms critically depends on the ability to transfer tractions across the interfaces and on their ability to maintain compatibility of deformations and the composite action of all components. Failure of those interfaces and the evolution of a debonding mechanisms has fatal implications on the performance of the sandwich structure and, even more important, on its safety. The criticality of the debonding mechanism becomes particularly prominent when the failure of the interfaces diminishes the sandwich action and yields a sudden release of elastic energy. This effect is directly converted into a rapid growth of the debonding crack with crack front velocities that may reach the order of 10^3 m/s [1-3], abrupt evolution of a new structural state with time scales in the sub-ms range, and a significant dynamic response.

The aforementioned characteristics clearly define the debonding failure as dynamic by nature. The analysis and design of sandwich structures therefore has to take into account the presence and the behavior of interfaces as well as their dynamic failure mechanism and its impact on the layered structure. Specifically, the analysis has to span between service state performance where the interfaces maintain the integrative nature of the sandwich structure and the ultimate state behavior where they govern the dynamic debonding mechanism.

An attractive concept that introduces interfaces into the analysis while reflecting the physics of their behavior and the potential debonding mechanism is the cohesive interface approach. The cohesive interface defines the tractions that evolve across the interface between two adjacent components as nonlinear functions of the interfacial displacement jumps across that interface (tangential slip and normal separation). The nature of the nonlinear traction-displacement jump relations is such that under relatively small levels of slip and separation, the system reacts in a quasi-linear form with a rather stiff interfacial behavior. This phase minimizes the displacement jumps in the sense of a penalty method aiming to maintain compatibility of deformations across the interface. Under increasing levels of slip and/or separation, the tractions grow up to a maximum and then decay up to total fading. This phase simulates debonding.

While the cohesive interface is a powerful analytical and computational tool, it is a phenomenological one that necessitates calibration and assessment of the governing parameters. The smallest set of such interfacial properties includes the characteristic length parameter that defines the point of peak traction, the specific work of separation (fracture energy), and the functional form of the nonlinear cohesive laws. Additional features are the tangential-normal coupling, different shear and normal fracture energies, different shear and normal critical displacements and strengths, damage accumulation, rate dependent effects, etc.

The concept of the cohesive interface can be directly implemented the structural model, but the determination of the interfacial parameters is a challenge that necessitates the combination of two critical components. The first one is a sound set of experimental observations, measurements, and data that quantifies the debonding failure mechanism. Due to the dynamic nature of that mechanism, the experimental basis has to reside in the dynamic region providing observations on the kinematics of the debonding process. The second component is an analytical model and its numerical counterparts. The model should reflect the physical features of the debonding phenomenon, host the cohesive interfaces, and quantify the response of the test specimens and the target application. Also here, the dynamic nature of the problem necessitates its handling using dynamic analytical and numerical methodologies. The combination of experiment and modeling aims at throwing light on the nature of the failure mechanism, provide a framework for its quantification, and set the rules for the assessment of the latent parameters of the structure.

The aim of this paper is twofold. First, it aims to explore, quantify, describe, and characterize the dynamic debonding phenomenon in layered and sandwiched structures. Second, it aims to set forth an approach for using the direct experimental observations and the analytical/numerical data regarding the dynamic nature of the debonding process for the characterization the latent properties of the cohesive interfaces implemented in the framework. The specific sandwich application that is investigated in this paper focuses on beams strengthened with externally bonded layers of FRP. The bonded FRP layer serves here as supplemental tensile resisting reinforcement while the layered layout that includes the original substrate beam, the FRP layer, and the adhesive layer defines it as a sandwich beam. The role that is played by the interfaces in such configuration, and the fact that dynamic debonding failures are among its most common and yet critical modes of failure, draw the attention to that type of application.

2. METHODOLOGY

Following the dual objective of the paper, the methodology adopted for achieving its goals also combines two components. The first one integrates analytical modeling, numerical methodologies, and experimental methods that are all focused on the dynamic interfacial failure of the sandwich beam. The analytical model is based on the extended high-order sandwich theory that is extended to account for the dynamic effects and the interfacial nonlinearity associated with the debonding mechanism [4-5]. The numerical approach converts the analytical model and its physical modeling concepts into a specially tailored high-order finite element form [1]. The experimental method uses four point bending tests of sandwich beams specimens made of steel, epoxy, and FRP for the detection of the interfacial debonding kinematics. This is achieved using high-speed photography, digital image processing, and detection of the movement of the debonding front in time and in space [2-3].

The second objective of the paper is faced by the development of an algorithmic approach that uses the experimental observations and the analytical/numerical tools for the interfacial characterization. Specifically, it uses the experimentally detected critical load and critical displacement where the debonding mechanism initiates, the duration of the process up to its arrest, the crack length at arrest, the averaged crack front velocity, and the temporal crack front velocity as features incorporated into the objective function. The characterization approach uses those experimental observations as target parameters for the calibration of the interfacial properties implemented in the analytical/numerical model. On the one hand, for simplicity, the implemented cohesive laws are taken in a rather simple form where the functional basis and the coupling effects are pre-determined, the shear fracture energy and the work of separation are equal, and the only “free” variables are the characteristic length parameter and the specific work of separation. On the other hand, the calibration algorithm resides in a highly nonlinear and dynamic regime that necessitates adequate analytical and numerical tools. The effectiveness of the aforementioned procedure is examined through comparison of the behavior described by the calibrated model and the one observed in an independent experiment. This aims to look into the dynamic aspects of the response and to explore additional features that are beyond the scope of the experimental method.

3. RESULTS

To illustrate the above methodologies, and mainly the experimental approach to the detection of the debonding kinematics, the experimental setup developed and presented in Mulian and Rabinovitch [2,3] is revisited. The setup is schematically illustrated in Fig. 1. A sketch of the tested specimen and a photo of the specimen on the testing rig before loading are also depicted in Fig. 1. The test specimen is a three-layer structural system comprised of a steel base plate, a 3-4 mm thick epoxy adhesive layer, and a 1.2 mm thick CFRP layer. The mechanical monitoring of the test specimen is limited to measurement of the load, the displacement of the loading piston, and the midspan displacement of the specimen. The main crack monitoring methodology uses high-speed photography with a rate of about 88,000 frames per second. The resulting snapshots are then digitally processed in attempt to trace the debonding front and thus to capture the debonding failure in progress. Analysis of the specimen, which is intentionally designed with some level of a-symmetry, reveals that failure is expected to initiate near the left FRP edge, take the form of an interfacial debonding, and propagate at the adhesive-substrate interface [2]. This allows focusing the monitoring efforts on the left side of the specimen aiming to capture the process in a smaller photographed window, see Fig. 1. More details about the experimental methodology and the test setup are given [2].

An illustrative set of experimental results [3] is shown in Fig. 2 where a set of snapshots taken by the high-speed camera at intervals of $11.36 \cdot 10^{-6}$ s is depicted. The green cross-marks shown in the figure designate the location of the crack tip. The processing of such experimental results allows tracing the evolution of the crack length and mainly the velocity of the crack front and its variation in time. The relevance of the experimental results is therefore threefold. First, it allows to gain insight into the debonding failure and to assess its dynamic nature. Second, it inspires the development of analytical and numerical models that can further explore the dynamic features of the response. Third, it provides direct experimental data that can be used for the calibration and validation of the analytical and numerical models and particularly for the detection of the latent properties of the interfaces. The three aspects, and particularly those that are focused on the interfaces, are at the focus of the current investigation.

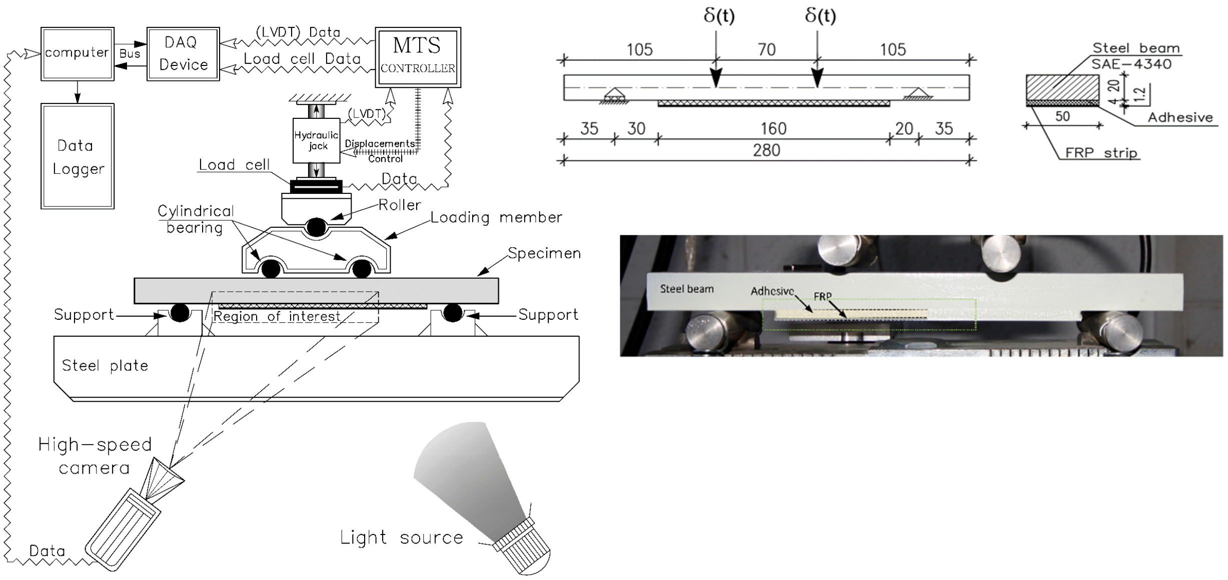

Fig. 1: Experimental setup and the test specimen (adapted from Mulian and Rabinovitch [2,3]).

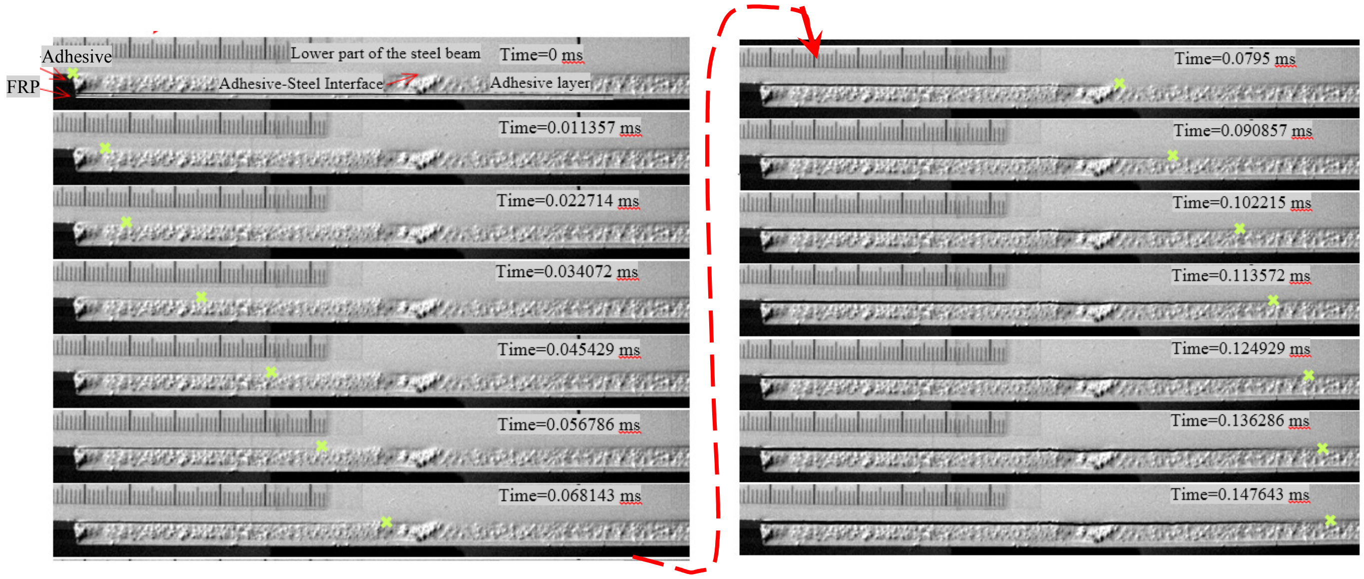

Fig. 2: Evolution of the interfacial debonding crack in time – experimental results (adapted from Mulian and Rabinovitch [3]).

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