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Inverse detection of constituent level elastic parameters of FRP composite panels with elastic boundaries using finite element model updating

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ABSTRACT

Fiber reinforced plastics (FRP) panels are extensively used in ship structures due to their superior specific stiffness and strength as compared to metals. However, their prolonged use may result in degradation of material properties as well as the boundary conditions; thus, affecting the dynamic performance. Moreover, the changes in material properties are mostly at constituent level, i.e. fiber or matrix. A vibration based inverse identification technique is proposed using finite element model updating to estimate the constituent elastic material parameters of FRP panels having elastically restrained boundary. The objective function is formed from the difference of experimental as well as finite element prediction of dynamic responses. A gradient based optimization viz. the inverse eigensensitivity method is implemented. A set of numerically simulated examples is presented to demonstrate that the prediction of material parameters can be grossly erroneous if the boundary elasticity is overlooked. The algorithm is found to be robust even when the 'experimental' data is sparse and contains random noise. The method can be used for condition assessment and damage detection of FRP ship panels. The technique is novel as for the first time constituent level elastic parameters of FRP panels having elastic boundaries are estimated from dynamic responses.

1. Introduction

Fiber reinforced plastics (FRP) are extensively used in weight sensitive applications, such as in the field of aerospace, marine, sports etc, due to their high specific strength and stiffness per unit weight (Daniel and Ishai, 2006). FRP being comparatively more durable and corrosion resistant than other conventional materials such as metals, it also is suitable for infrastructural applications, especially in highly corrosive environment of chemical plants, bridges built near seashore, etc. Since modern ship structures demand both weight sensitivity as well as durability, application of FRP in ship industry is ever increasing. Apart from the main hull of small ships, compartment separators, decks etc. of even bigger ships are now-a-days made of FRP type of layered composites. FRP deck panels are also heavily used in both onshore and offshore structures other than ships, such as in floating docks, oil drilling platforms, parts of harbors etc. The dynamic performance of such structural components is extremely important from safety, vibration serviceability and operational point of view and depends upon the material properties, existing boundary conditions and geometry. The correct assessment of dynamic behavior depends upon the availability of accurate information about all the above components, out of which the material and boundary parameters are the most uncertain sources of error, especially after a long period of existence of a structure in exposed environment. Usually a detailed finite element model is used to model such structure and it can incorporate geometrical intricacies to a high degree of accuracy. Usually glass fibers (e.g. E-glass mats in the form of woven roving or chopped strand mats) and polyester or epoxy resins are used as fibers and matrix respectively. Unlike isotropic materials, structural fabrication and material fabrication are one unified process for FRP structures. Curing techniques also vary from place to place. Labor intensive hand-lay-up process induces variable and high level of uncertainties into the material properties. The two main sources of information to get material data are the information supplied by manufacturer and the standard handbooks-both of them can differ significantly from the actual existing material constants which could finally be achieved. The standard method to get somewhat accurate material property data for specific application is to conduct static characterization tests on small samples prepared from that particular batch of materials used. Such characterization tests at constituent level, i.e. at the

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fiber and matrix level are even more cumbersome to perform due to the stringent requirement of sample preparation. The future trend of application of FRP type of composites in Ship industry demands use of different materials in layers to cater to required level of stiffness; thus making the material characterization process even more laborious. But, most importantly, these material parameters can vary significantly over ages during the long term operation of the structure due to natural degradation of material properties. Thus, although accurate initial material data can be made available during the commissioning of the ship, the values will change significantly over time. Most FRP components in ship structures are used as stiffened panels and their actual boundary conditions may differ significantly from any classical description, such as fixed or simply supported etc. Most likely the flexibility at the boundary of such panels will be sufficient to consider it as elastic and not perfectly 'fixed'. Again, like material properties, these boundary conditions also get changed substantially due to prolonged use, mostly becoming more flexible over time. For ship panels, they are most likely to become more flexible axially as well. All these errors from material properties and boundary conditions may pervade the numerical prediction of dynamic behaviour of FRP panels using even the best finite element model to such an extent that the results could be simply misleading. Any long term and non-destructive condition assessment or damage detection exercise on FRP panels of ship structures need to address these issues properly before framing any effective health monitoring strategy.

There is no established direct method to determine material properties of existing FRP structures, as samples cannot be extracted. It also appears that there perhaps is no convenient method to measure boundary flexibility of existing structures directly. The traditional approach in engineering to predict the dynamic responses of any structures is to solve a forward problem, where the existing material properties and boundary conditions are 'believed' to be not deviating much from their initial conditions and the designer takes the risk that they are not. The problem can only be solved accurately through a mathematically well posed inverse problem with the aid of additional (but convenient) experiments to determine the changed (unknown) system parameters (material parameters and boundary conditions in this case). Mostly, such inverse problems are solved iteratively as a series of forward finite element model updating problems, using optimization techniques. The current state-of-the-art suggests case studies relevant to particular application area. For FRP structures in ships, non-destructive vibration modal testing can be conducted easily in a very short period of time, it may also be possible to conduct such tests without disturbing much the normal operation of the ship.

The concept of using experimental modal testing data (Ewins, 2000) in combination with finite element modeling to estimate parameters which are otherwise difficult to observe directly is already in existing literature and current practice (Mottershead and Friswell, 1993). The method is mentioned also as mixed numerical-experimental techniques (MNET) (Rikards et al., 1999; Lauwagie et al., 2004) in current literature. Measuring average homogenized material property parameters in layered FRP composites are also plenty in literature (Frederiksen, 1997; Rikards et al., 2001). But the present state-of-the art of modal testing almost universally advocates the free-free boundary conditions in laboratory as most applications are restricted to small scale structures or machine components or samples solely for instant material property identification of developed complex materials. The application so far has not focussed its attention to existing structures, which are somewhat bigger as compared to laboratory specimens and also fixed elastically to other components. Also, long term changes of material parameters were never on focus. It is rather a necessity for the present application of inverse problem that the existing FRP structural component in ship, such as a panel be tested dynamically as a whole to measure its global dynamic responses and the elastic properties are updated from initial guesses in presence of elastic boundary conditions. Any subsequent prediction of dynamic responses using this updated finite element model will be much more realistic and will be able to distinguish real damage situation from false implications resulting from changed boundary conditions.

Early examples of updating finite element models by processing dynamic test data (Mottershead and Friswell, 1993) to determine average material properties of small scale samples of composite materials used natural frequencies and mode shapes as indicators (De Wilde et al., 1984; Deobald and Gibson, 1988; Mota Soares et al., 1993; Moussu and Nivoit, 1993; Grediac and Paris, 1996; Larsson, 1997). Even recent applications (Matter et al., 2007; Pottier et al., 2011) focus on identification of the in-plane elastic constants of a homogenized equivalent single layer, i.e. E_1, E_2, G_{12} and ν_{12} from non-destructive vibration test on small scale samples only. Chakraborty and Mukhopadhyay, (2000a, 2000b), and later on Chakraborty et al. (2002), have extended the idea of determination of material constants to layered FRP stiffened plates. Ismail et al. (2013) have recently estimated material parameters of orthotropic plates with various combinations of classical boundary supports using frequency information only.

Application of material property identification to real structures is rather scarce. Dascotte (1992) determined the average in-plane elastic constants of vertically stiffened composite cylindrical shells. Felix et al. (2003) investigated an interesting problem of evaluation of repaired steel panels with patch of orthotropic composite materials. Cugnoni et al. (2007) estimated the in-plane properties of E-glass/polypropylene laminate using both frequency and mode shapes. Alagusundaramoorthy and Reddy (2008) have investigated the static performances of FRP panels made by hand lay-up. Raney et al. (2011) described a method for in situ identification of material parameters for layered structures based on carbon nanotube arrays. Inverse detection of material parameters for FRP structural components in a ship in operation, especially at constituent level is non-existent in current literature.

Differences in dynamic responses of structures with elastic boundaries have been reported in literature mostly as forward problems for isotropic and anisotropic plates (Laura et al., 1977, 1979, 2014; Warburton and Edney, 1984; Grossi et al., 1985). All such early investigations finally lead to searching approximate admissible functions representing the true displacement (and rotational) behaviour at boundary of mainly rectangular plates (Zhang and Li, 2009; Jin et al., 2010). A more recent valuable reference is due to Khov et al. (2009). Vibration responses of plates having elastic rotational restraint in harmonic loading condition have been investigated by Mukhopadhay (1981). Okan (1982) investigated the fluid effects in orthotropic rectangular plate vibrations in connection with vibration of ship plating with one edge free while the rest of the boundaries are elastically restrained. Determination of modal properties of real ocean structures is very rare. Li et al. (2012) has recently attempted to estimate the frequencies and damping ratios of a jacket platform from noisy free vibration data.

The inverse approach of determination of boundary flexibility is rare. Friswell and Mottershead (1995) determined boundary translational and rotational stiffnesses and flexural rigidity of an aluminum cantilever beam from frequency information. Modal stiffness based error function approach has been used by Sanayei et al. (1999) to estimate the flexibility of joints, both at supports as well as at connecting members of bridges. Ahmadian et al. (2001) proposed a methodology based on solution of reduced order characteristic equations to update both translational and