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A dynamic analysis approach for identifying the elastic properties of unstitched and stitched composite plates

Nan Li *, Mabrouk Ben Tahar, Zoheir Aboura, Kamel Khellil

Sorbonne universités, Université de technologie de Compiègne, CNRS, UMR 7337 Roberval, Centre de recherche Royallieu, CS 60319, 60203 Compiègne cedex, France

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ABSTRACT

The identification of elastic properties from the dynamic behavior of structure has long been an alternative method to mechanical test. This method can avoid the variability of properties due to extraction of the specimen and achieve better homogenization by involving the whole structure. The mode classification is proposed and integrated in the identification process in this paper and helps to reduce the calculation time.

Firstly, the measured frequencies are provided by vibration test while the calculated frequencies are provided by a finite element model with discrete Kirchhoff plate element. Then a mode classification process is conducted to accelerate the identification. Every constant is identified by minimizing the difference between the calculated and the measured frequencies of the group that it dominates. This method has been applied to two types of composite plate: unstitched plate and dispersedly stitched plate which presents both macro and meso heterogeneity. The limited dimension along the width direction of the stitch makes the modulus inaccessible by mechanical test and thus this dynamic method turns to be indispensable.

1. Introduction

The composite materials are widely used in various industrial fields nowadays such as automotive, rail industry and aerospace. Composite materials will account for more than 50 percent (by mass) of the new generation of aircraft in the future. The wide utilization is mainly due to their high stiffness/mass ratio. However, the variety of constituents and molding technique of composite materials lead to a great diversity of their properties. On one hand, this characteristic brings us a certain degree of freedom in the optimization of their performance according to different areas of applications and desired functionality; on the other hand, it requires identification for each configuration of fabrication.

The mechanical test is a traditional way to identify the elastic properties. For composite materials which are heterogeneous, the specimen is sometimes not big enough to achieve a satisfied level of homogenization. In addition, the exact values of some properties are difficult to obtain by classical mechanical test such as the in-plane shear modulus of a thin plate.

To overcome the difficulties in the identification of elastic properties of composite materials, an alternative method of identification from the vibration behavior has been proposed in the last two decades. The vibration behavior of a structure is controlled by the elastic properties (as the geometry and density are known in most cases). Inversely, the elastic properties can be determined by the vibration behavior via a sufficiently accurate model. Based on this principle, the identification is realized by minimizing the difference between the measured result of vibration behavior and a result calculated by a model. Compared to a traditional mechanical test, this approach presents several advantages:

- For composite materials, the elastic properties are several independent constants. For example, 4 constants are needed to determine the stress-strain relation of an orthotropic plate under plane stress. With the help of this method, all the constants can be simultaneously identified (including the shear modulus).
- Bigger and more representative specimen enables a more satisfied level of homogenization. In contrary to mechanical test, local imperfections of structure bring little influence to the result of this method.
- The frequency dependence of elastic constants can be taken into consideration by this method.

* Corresponding author.
E-mail address: nan.li@utc.fr (N. Li).

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The development of this identification method involves the evolution of model, the algorithm of optimization and the experimental instrument. The early work usually used an analytical model instead of a finite element model. Deobald and Gibson [1] used the Rayleigh–Ritz technique to model the vibration of rectangular orthotropic plate. Abrate and Perry [2] developed approximate expressions of the first six natural frequencies and used these expressions to provide initial values of the elastic properties for the Rayleigh–Ritz model. The finite element model has been introduced to this identification method in later works. A finite element model based on higher order assumed displacement field has been developed by Araujo [3] and a commercial finite element code has been adopted by Shun-Fa Hwang [4]. Another direction of evolution is the algorithm of optimization. Sol [5,6] considered the elastic properties as stochastic values and introduced a statistical optimization method into the identification process. His work has been extended to laminated plates [7] and sandwich beams [8]. Two different estimators, Bayesian estimator and minimum variance estimator, have been used and compared by Daghia [9] in the optimization process. Bledzki [10] and Rikards [11] have mentioned the utilization of experiment design which enables the construction of response surface based on only the reference points. A hybrid genetic algorithm has been used in the optimization by Shun-Fa Hwang [12]. As to the experimental instruments, evolution focuses on imposition of excitation and capture of response. For the excitation instruments, hammer [1], shaker and loudspeaker [13] are commonly used. The hammer-impact is a zero mass loading method and can give a broadband excitation to the structure in a short duration. However, the direction and magnitude of the excitation are difficult to control. As to the shaker, the frequency range excited and the level of force applied are easily controlled. In this case, attention should be paid to the influence brought by the excitation system (shaker, stinger and transducer) for light/flexible SUT (structure under test) [14,15]. The loudspeaker can avoid damage to fragile structure [16] as it is non-contact but the excitation imposed is distributed and it is difficult to measure the force transmitted to the structure accurately. As to the capture of response, the accelerometer is commonly used as contacted sensor[4]. The non-contact instruments such as laser vibrometer (single-point vibrometers, scanning vibrometers) [17,13,18] and microphone [19] can avoid adding mass to the system. Among these non-contact instruments, the measurement of microphone is indirect as it actually measures the pressure; sing-point vibrometer can only measure the vibration on single point while the scanning vibrometer can measure the vibration of plenty of points automatically. A couple of combinations of excitation and capture instruments are possible. The best combination may be the hammer and the scanning vibrameter. However, specific measuring setup is necessary. For example the auto–hammer to make the excitation reproducible proposed in [20]. In addition, the setup to reduce post-strike rigid body motion is also needed in the case of vibration under free-free boundary condition. In our case, the combination of scanning vibrometer/shaker is chosen although the influence of the excitation system should be taken care of. This combination is commonly used in laboratory and the setup is easy to install. In addition, the errors and uncertainties of the whole identification have also been studied by several researchers. Frederiksen has discussed various sources of errors in detail in [21]. Lauwagie [22] has studied the relation between the uncertainty of input parameters (for example the measured resonance frequencies) and the uncertainty of the output parameters.

The researchers in this domain always try to identify all the parameters at the same time and have not tried to identify the parameters one by one. They are always bothered by the calculation time. For a plate with 4 elastic constants, the parameter space is already four-dimensional. Although different algorithm of optimization can accelerate this process, the calculation time is still large.

The classification of modes and identification of parameters one by one can help to solve this problem (the details will be presented in Sections 4 and 5). Each parameter is identified by a group of modes which it dominates. The dimension of the parameter space has been reduced to 1 and consequently the calculation time is reduced. The modes which is more complex (bending modes along two direction or torsion-bending mode) involve more than one parameter will be used to validate the robustness of this method.

This approach is proved to be effective on both unstitched plate and dispersedly stitched plate which presents both macro and meso heterogeneity. According to the authors, the characterization of stitched composite by vibration test has not been presented in the literature.

The assembly of composite structure by stitches is an interesting alternative to riveting and adhesion. Jegley [23] has shown an interesting contribution of the stitch to the buckling resistance of the stiffened structure assembled by stitches. Tan [24] has also demonstrated that the stitch can improve significantly the damage tolerance. Generally speaking, the employment of stitch is becoming widespread and brings composite materials an added-value which has been mentioned in many literatures, including but not limited to [25–28].

The mechanical characterization of stitched zone is very delicate. In fact, the zone of assembly (Fig. 1) always has very limited width (only includes several stitches). Consequently, it is very difficult to extract specimen for traditional mechanical characterization. In addition, the motif of stitch always makes the mission more complex, particularly the definition of representative elementary volume (REV). The determination of REV is in fact indispensable to mechanical tests. In the case of one-side stitching (Fig. 3), the extraction of specimen in the transverse direction is not possible due to the special motif of this technique. So it is necessary to find a new alternative for the characterization of the zones which include this type of stitch. The identification method from vibration test we present in this paper is one of these alternatives.

2. Finite element model

The accuracy of the finite element model is a prerequisite of this method. For a thin plate, the Kirchhoff hypothesis is widely used in the literature. The discrete Kirchhoff elements started from Discrete Kirchhoff Triangular element (DKT) [29] and Discrete Kirchhoff Quadrilateral element (DKQ) [30] and have formed a big family [31]. Base on the DKQ element, a discrete Kirchhoff

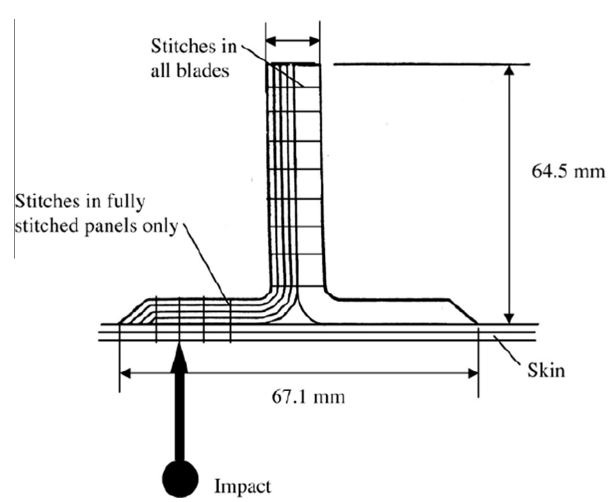

Fig. 1. Stitches in the assembly of composite structure.