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Tolerance synthesis of fastened metal-composite joints based on probabilistic and worst-case approaches[☆]

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ABSTRACT

Variabilities in geometrical and material properties occur systematically after manufacturing and joining operations on different parts of an assembly. The behaviour and structural performance of composite/composite or composite/metal fastened joints are particularly sensitive to some of these variabilities. Controlling the effect of variabilities by tolerancing uncertain parameters is therefore crucial to avoid the failure of the structure. However, performing a variability study is generally costly because a large number of configurations need to be evaluated, especially when the behaviour model of the system is a numerical one.

This paper presents an approach for tolerance synthesis of uncertain parameters in fastened metal-composite joints. The low time-cost of the approach is ensured by using a reduced finite element model of the joints and a strategy to reduce the number of calculations. Both probabilistic and worst-case approaches for the propagation of uncertainties can be applied through the proposed tolerancing synthesis. An allowable tolerance value for an uncertain parameter can then be easily calculated by identifying an analytical law which links tolerance to a structural performance criterion. The robustness of the proposed approach is illustrated by its application to a 4-bolt metal-composite single-lap joint where several sources of variability are introduced (i.e. hole-location error, pin/hole clearance, fastener preload).

1. Introduction

Joining structures is an operation both to maintain two or more parts in position and to transfer loads between them. Both functions are made possible thanks to various joining technologies, such as bonding, welding or fastening, with fastening being one of the most ancient and commonly used joining techniques. This technology allows the transfer of high loads through mechanical connections while maintaining a removable assembly and easy monitoring.

Sizing fastened joints is generally based on deterministic methods and consists in considering only the nominal geometric and material properties of parts. Although this approach is widely used by designers, it remains improvable. In fact, errors in design parameters (i.e. gap between nominal and actual values) are systematically obtained after manufacturing. The difference between targeted and actual properties may therefore give misleading expectations of the joint behaviour. To ensure the desired structural performance and avoid failure, the effect of these uncertainties is generally addressed by applying margins to an allowable load obtained with standard tests and by requiring tight tolerances to the process department.

The behaviour of fastened composite joints is particularly sensitive to geometrical variabilities such as fastener-hole clearance and hole-location errors [1–4]. Contrary to the classical joining process for metal parts, the axial preload applied to composite parts is generally low, not only for fear of damaging the material during tightening but also because of the relaxation phenomenon, which leads to a decrease in fastener preload with time [5]. This low preload involves a loss in adherence during loading and therefore leads to a load transfer mode principally through the pin/hole contact. However, this sliding phase preceding the pin/hole contact depends essentially on the distance between contact surfaces. Having different clearances and hole-location errors consequently creates an imbalance in the distribution of loads between fasteners and eventually an overload on some fasteners. This uncontrolled overload may be the cause of a structural failure. Controlling these variabilities is therefore a crucial issue to ensure structural integrity without systematically employing a complex assembly grid combined with expensive apparatus in order to respect tight tolerances.

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Analysing the effect of geometric and material variabilities on joint performance requires an efficient behaviour model. This physical model should be able to model the main phenomena required to estimate structural performance while enabling a low calculation time in order to perform the propagation of uncertainties. Ensuring these conditions becomes complicated with the presence of complex part geometries and non-linear phenomena as contact. This is the main problem which makes it difficult to produce such a variability analysis.

Most variability analyses to be found in the literature are therefore performed under the assumption of rigid (not deformable) parts. In this case, designers generally try to calculate optimal tolerances to ensure geometric constraints as mountability and position of parts after joining [6–11]. However, when the main design criteria depend on load distribution and are managed by part deformation, a structural analysis, including material behaviour, should be employed. With the increase in computation capacity in the last decades, there are now a few studies dealing with the effect of variabilities on complex structures with the help of structural analysis. Söderberg et al. [12] studied the effect of geometrical variabilities on the resistance of a composite wing box during assembly based on the Monte Carlo method. However, concerning fastened structures, only sensitivity studies, limited to the analysis of a few parameter values, can be found. For example, McCarthy et al. and Gray et al. [13–15] have examined the effect of bolt-hole clearance and bolt-torque on load distribution and failure in single- and multi-bolt composite joints by performing ten or so simulations. However, to obtain statistical quantities, such as the failure probability associated with the tolerances of uncertain parameters, hundreds of configurations should be simulated.

In order to ensure the feasibility of such an analysis of uncertainties in fastened joints, Askri et al. [16] recently proposed a reduced fastener model based on Multi-Connected Rigid Surfaces (MCRS). This model is able to take relevant phenomena into account while reducing the calculation time by about 80% compared to a 3-D model made of solid finite elements.

This paper therefore aims at evaluating the ability of this model to perform the propagation of uncertainties required for the development of a tolerance synthesis. The use of different techniques to propagate uncertainties, such as the Monte Carlo method, raises several issues even if the model selected agrees with prediction quality and computation time requirements. Simulating many joint configurations needed to perform the tolerance analysis requires a robust reduced model especially in terms of model building and convergence of non-linear calculations. In addition, the number of configurations needed to fulfil the propagation of uncertainties should be studied according to the desired precision, the total calculation time and the number of uncertain parameters. To determine the optimal tolerance regarding the targeted mechanical performance, several uncertainty propagations considering different values of tolerance needs to be performed. Depending on the method used, calculation time can be prohibitive.

In this paper, a general description of the proposed tolerancing approach is first presented to show the different tools and methods used and the interaction between them. These tools and methods are then detailed through a case study where only one source of uncertainties is considered (i.e. hole-location errors). In the last section, the use of the approach to design a joined structure in an uncertain context is discussed, taking into account several sources of uncertainties (i.e. hole-location errors, pin/hole clearance and fastener preload).

2. Proposed approach

Computation time is the main obstacle to the propagation of uncertainties in fastened structures. This cost is due to the time required to evaluate one configuration defined by a set of input parameters but also to the total number of calculations needed to simulate the effect of uncertainties.

In this section, we first show how the calculation time for a single configuration could be decreased using a reduced behaviour model of the joint. Next, we focus on the definition of a tolerancing approach based on the reduced model. The implementation of the proposed tolerancing approach in a design process is then detailed.

2.1. Joint behaviour model

Concerning the cost of a single calculation, the calculation time depends mainly on the model selected for the joined structure. Due to the complexity of the physical phenomena related to joint behaviour and the need for an accurate modelling of these phenomena, the use of a solid 3-D finite element model is generally preferred. However, due to the large number of degrees of freedom generated by this type of model, calculation time becomes prohibitive as soon as the number of fasteners increases.

Several reduced joint models can be found in the literature. The most popular one, which is generally used by engineers to model large fastened structures, is based on a representation of fastener geometry and behaviour by a connector element linking the two parts of the joined structure [17,18]. Despite its low computation time compared to 3-D models, the use of this simplified model is generally restricted to deterministic studies. Indeed, the behaviour law of the connector element, which includes many phenomena such as contact, clearance recovery, fastener preload, depends on geometric, material and contact parameters. Whatever method is used to identify the behaviour law, from experimental tests [17] or from local 3-D models [18], the law should be re-identified if a parameter in the joint changes. This modelling approach becomes very costly and therefore it is unsuitable for the propagation of uncertainties.

To find a compromise between the ability of the model to deal with variabilities and the calculation time, Askri et al. [16,19] have developed a reduced finite element model based on structural elements and shell theory. Thanks to the explicit modelling of the fastener and its interaction with parts, the joint model does not need a re-identification of any parameter when variability is introduced. Thus, the model proposed by Askri et al. is well adapted to the propagation of main uncertainties in a fastened joint such as clearance or fastener preload.

The construction of the MCRS fastener model is based on a physical approach where deformation modes are studied in order to define the relevant simplified geometry and kinematic behaviour. As a result of this study 4 rigid surfaces are defined, representing contact surfaces in a bolt: 2 surfaces for the head (HS_1 and HS_2) and 2 surfaces for the pin (PS_1 and PS_2), as shown in Fig. 1. Two rotational degrees of freedom are considered between head and pin surfaces to take into account the rotation of heads due to the location of bending deformations in the junction between head and pin. Three translational degrees of freedom are also introduced in the connection between the two pin surfaces to take axial and transverse deformations into account. Each degree of freedom is associated to an equivalent stiffness by defining three connectors. These equivalent stiffnesses are identified using a 3-D solid element simulation through an approach based on both equivalent displacement versus resultant forces response and elastic strain energy.

The reduced model has demonstrated a high capacity to take relevant phenomena into account and to provide interesting mechanical quantities with a low calculation time compared to a traditional 3-D solid elements model. The saving in calculation time is around 80%. Note that error related to modelling is not taken into account in this paper, but it could be integrated as an additional source of uncertainties, as proposed in [20]. Error related