Computational Strategy for the Analysis of Bolted Joints Taking Into Account Variability

L. Champaney, Pierre-Alain Boucard, S. Guinard

Computational Strategy for the Analysis of Bolted Joints Taking Into Account Variability

L. Champaney[a], P.A. Boucard[b] and S. Guinard [c]

[a] *LEMA - Univ. de Versailles/CNRS, 45 av. des États Unis*

78035 Versailles Cedex - France

[b] *LMT Cachan - ENS Cachan/CNRS/Paris VI, 61 av. du Pt Wilson*

94235 Cachan - France

[c] *EADS-CCR, 12 rue Pasteur - BP76*

92152 Suresnes Cedex - France

Abstract

The aim of the present work is to develop an efficient strategy for the parametric analysis of bolted joints used in the aerospace area. They are used for elastic, structural assemblies under quasi-static loads, with local nonlinearities such as unilateral contact with friction. Our approach is based on a decomposition of the assembly into substructures and interfaces. The problem on each substructure is solved by the finite element method and an iterative scheme based on the LATIN method is used for the global resolution. The strategy proposed consists in calculating response surfaces such that each point of a surface is associated with a design configuration. Each design configuration corresponds to a set of values of all the variable parameters (friction coefficients, prestress) which are introduced into the mechanical analysis. Here we propose, instead of carrying out a full computation for each point of the surface, to use the capability of the LATIN method to re-utilize the solution to a given problem (for one set of parameters) in order to solve similar problems (for the

other sets of parameters).

Key words: Uncertainties; Assemblies; Contact; Friction; Substructuring Method; Multiresolution; LATIN method

1 Introduction

The solutions to deterministic problems are often calculated by finite element analysis (FEA). For structural engineers, the incorporation of parametric uncertainties of a system into a mechanical model represents a challenge; however, without this information, the structural response could not be analyzed accurately, particularly in terms of reliability. These parametric system uncertainties may affect the mechanical and geometric properties, the boundary conditions. In the case of structural assemblies, ones knowledge of the friction coefficients or of the stiffness of bolted joints is especially poor. In order to take such uncertainty into account, it is necessary to calculate the response of the structure for all possible sets of values of the design parameters or to use a probabilistic structural analysis approach [1]. The numerical examples presented in the paper concern 3D bolted joints. For some of these examples, over a thousand different calculations had to be carried out for the parametric study. The comparison of the computation costs with those of classical industrial codes shows the algorithm is very efficient.

2 The LATIN method

Here, we will review only the main aspects of the LATIN method. The details of the method itself can be found in [2] and those of its particular application to computational contact problems in [3].

2.1 Decomposition of an assembly

An assembly is composed of a set of *substructures* (each substructure is a component of the assembly) which communicate with one another through *interfaces* (each interface represents a connection). Each interface is a mechanical entity with its own variables and its specific behavior which depends on the type of connection. Many different connection types can be modeled by this approach, but in this paper we consider only classical contact connections.

2.2 The LATIN algorithm

A LATIN (LArge Time INcrement) approach [2] is used to solve the problem. The solution of the problem is written as a set of time-dependent fields on each substructure and related interfaces. The LATIN approach is based on the idea of isolating the difficulties in order not to have to solve a global problem and a nonlinear problem at the same time. The equations are split into two groups with the following two sets of solutions:

- the set $\mathcal{A}_d$ of solutions to the linear equations related to the substructures
- the set Γ of solutions to the local equations (which may be nonlinear) related to the interfaces

The search for the overall solution (i.e. the intersection of the two sets) is conducted iteratively by constructing approximate solutions s which verify the two groups of equations alternatively on the complete time history. Thus, each iteration in the process is composed of two stages:

Local stage: for $s_n \in \mathcal{A}_d$ known, find $\widehat{s}$ such that:

$$\widehat{s} \in \Gamma \qquad (interfaces) \tag{1}$$
$$\widehat{s} - s_n \in E^+ \qquad (search\ direction) \tag{2}$$

Global stage: for $\widehat{s} \in \Gamma$ known, find s_{n+1} such that:

$$s_{n+1} \in \mathcal{A}_d \qquad (substructures) \tag{3}$$
$$s_{n+1} - \widehat{s} \in E^- \qquad (search\ direction) \tag{4}$$

In our particular case of linear elastic substructures, the inner solution (in displacement and in stress fields) can easily be calculated from the boundary values. Therefore, from here on, a solution s will be represented only by the force and velocity fields on both sides of an interface.
The search directions are chosen such that the convergence of the algorithm is ensured [2]. An error indicator is used to control the convergence of the algorithm. This indicator is an energy measure of the distance between the two solutions s_n and $\widehat{s}$.

3 Approach proposed

The approach proposed consists in calculating response surfaces ([4], [5]) such that each point of a surface is associated with a design configuration. At each iteration, the LATIN method leads to an approximate solution to the problem over the whole time interval. Therefore, the trick is to reuse this approximation (associated to one set of values of all the design parameters) to find the solution to another design configuration (another set of the design parameters) similar to the one for which it was calculated in the first place.

Our multiple solution method uses the fact that the LATIN algorithm can be initialized with any solution (usually an elastic solution) provided that it verifies the admissibility conditions. Therefore, the key to our technique is to initialize the process associated with a new design configuration using the results of the calculation carried out on the first set of values of the design parameter. In this manner, a first approximation of the solution to the new design with a strong mechanical content is immediately available from the start. In this particular case of elastic structures in contact, the interfaces play a vital role: they enable one to initiate the calculation on the new design configuration without having to save all data on the substructures as well as to search for the solution of the new design configuration with an initial solution well-suited to the target problem. In the best-case scenario, only a few iterations are necessary: the solution to the problem is obtained at low cost. If the solutions to the design configurations are close enough, the latter can still be derived at a significantly lower cost than by using a full calculation. For the parametric study presented herein, we just change the parameters between iterations. Thus, the new computation is initialized by the solution to the previous one. If the parameters change slowly, the two solutions are close and only a few iterations are needed to reach convergence in the new calculation. This strategy have already been succesfully used for 2D assembly in [6].

4 Example - A 3D assembly

A bolted joint is considered, the dimensions of the studied part of the connection are presented on Fig. 1. The study case was derived from tests conducted at EADS-CCR (Suresnes, France) on 4 bolts junctions (see Fig. 2). Experiments confirmed the sensitivity of life expectancies of such junctions to frictions, pre-tensions in the bolts, clearances... These parameters have a natural scattering, and a full experimental campaign for assessing their effective influence would result in high numbers of specimens. This motivated EADS-CCR to investigate a more cost-effective numerical approach with LMT Cachan.

The connection between three plates is assumed by two prestressed bolts.The bolts and the plates are composed of the same material (Youngs modulus $E = 200000MPa$ and Poissons coefficient $\nu = 0.3$). The prestress of the bolts is assumed by a relative displacement between the body and the head of each bolt. The two relative displacements are denoted g_1 and g_2 (Fig. 1) and the friction coefficient is denoted μ. In the parametric study, we study the influence of the prestress of the bolts and of friction on the transmission of forces. The same Coulomb friction coefficient is used on each contact zones. There is thus three parameters : one friction coefficient and one prestress in each bolt. The friction coefficient can take 9 different values (0.1 to 0.5 , step 0.05). The prestresses can take 12 different values ($0.05mm$ to $0.3mm$, step $0.025mm$). For the complete parametric study, 1296 computation have thus to be performed.

The same mesh have been used for all the computations. It is presented on Fig. 3. It is composed of 10 705 linear elements (pyramids or bricks) and 8 090 nodes. The total number of degrees of freedom is then 24 270. This number does not included the possible additional contact variables (Lagrange multipliers). The computation is carried out on two steps:

- step 1: pre-stress of the bolts (duration 1s - 1 time increment asked).
- step 2: application of the load (duration 1s - 10 time increments asked).

In order to estimate the capabilities of the LATIN method for the treatment of frictional contact problems a comparison with the industrial finite element code ABAQUS have been carried out on one parametric configuration ($g_1 = 0.05mm$, $g_2 = 0.025mm$ and $\mu = 0.3$). Fig. 3 presents the comparison of the global response of the connection (displacement of one point of the loaded surface). The ABAQUS and the LATIN solutions are very closed.

For convergence reasons ABAQUS solver ran more time increments than asked (10 for step 1 and 62 for step 2). The results of the comparison are presented in Tab. 1. One can notice that on this single computation the LATIN method is 10 times more efficient than a classical Finite Element code. This efficiency, in terms of size of the problem and in term of computational time, as already been shown and discussed in [7]. Fig. 4 and Tab 2 summarizes all the realized calculations. The evolution of the maximum transmission force is plotted for each value of the friction coefficient μ as a function of the two prestress of bolt g_1 and g_2. One can notice that the force varies slowly according to the prestress, but strongly according to the friction coefficient.

Using the surface response, we can now easily determine the optimal set of parameters (prestress, friction coefficients) by comparing the numerical and the experimental results. This work is in progress.

5 CONCLUSIONS

The proposed approach based on the LATIN method can be very efficient numerically because the uncoupled treatment of the local and global problems leads to a considerable reduction of problem sizes. Another important point is that the linear systems corresponding to the substructures are independent of one another and could be solved in parallel very efficiently. The strategy is based on the capability of the LATIN method to reuse the solution to a given problem in order to solve similar problems. Numerical examples showed the very good behavior of the algorithm applied to the case of multiple resolutions in the analysis of 3D assemblies. The solution to the initial problem is a very good starting point for the calculations conducted on other problems provided that these calculations do not exert excessive perturbations on the response. Moreover, the interfaces play a vital role in allowing a considerable reduction of the computation costs. This approach is quite general by nature and should be applicable to a number of other nonlinear problems.

References

[1] H. Benaroya, M. Rehak, Finite element methods in probabilistic structural analysis: A selective review, Applied Mechanics Review 41 (5) (1988) 201–213.

[2] P. Ladevèze, Nonlinear Computational Structural Mechanics, New Approaches and Non-Incremental Methods of Calculation, Springer Verlag, Berlin, Germany, 1999.

[3] C. Blanzé, L. Champaney, P. Védrine, Contact problems in the design of a superconducting quadrupole prototype, Engineering Computations 17 (2-3) (2000) 136–153.

[4] M.-R. Rajashekhar, B. R. Ellingwood, A new look at the response surface approach for reliability analysis, Structural Safety 12 (1993) 205–220.

[5] L. Faravelli, Response-surface approach for reliability analysis, ASCE Journal of Engineering Mechanics 115 (12) (1989) 2763–2781.

[6] P.-A. Boucard, L. Champaney, A suitable computational strategy for the parametric analysis of problems with multiple contact, Int. J. Num. Meth. Engng. 57 (10) (2003) 1259–1281.

[7] C. Blanzé, L. Champaney, J.-Y. Cognard, P. Ladevèze, A modular approach to structure assembly computations. application to contact problems, Engineering Computations 13 (1) (1995) 15–32.

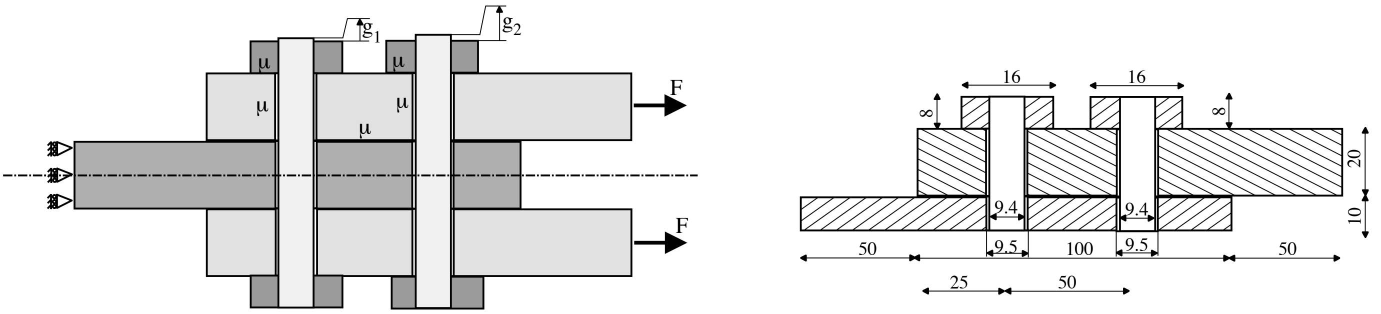

Fig. 1. Scheme of the structures and dimensions thickness: 40 mm

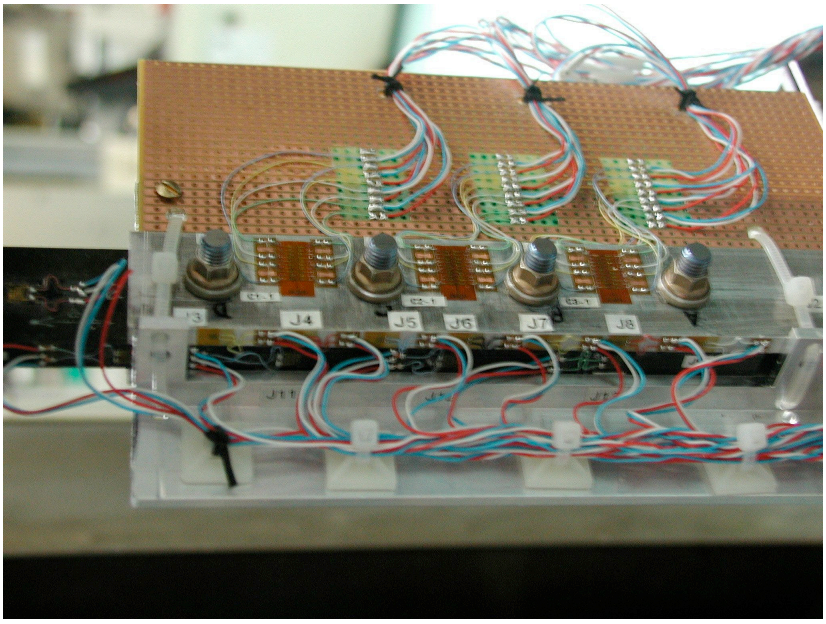

Fig. 2. Real test carried out at EADS-CCR

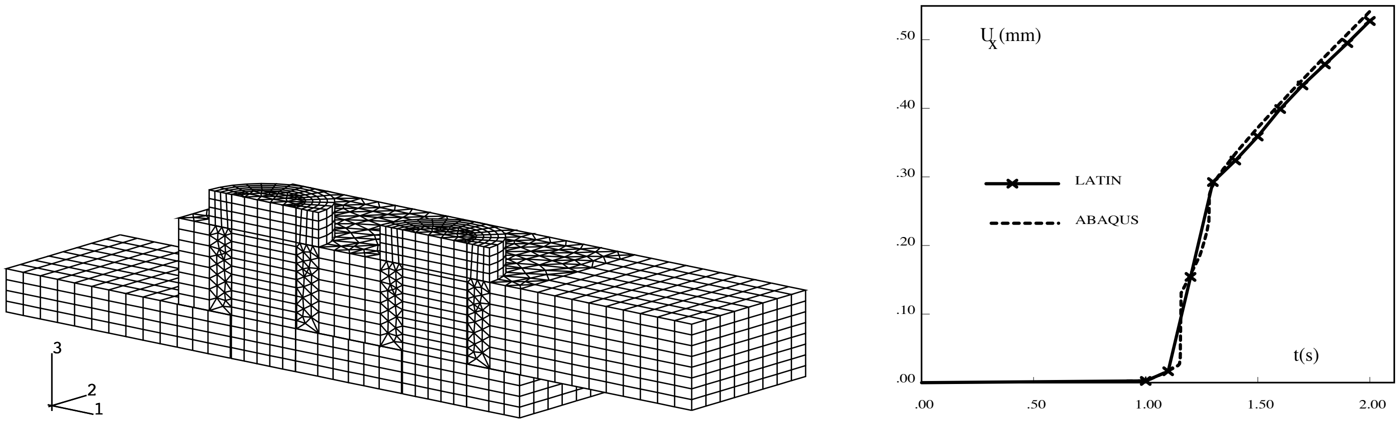

Fig. 3. Mesh of the assembly and Displacement of one point of the loaded surface

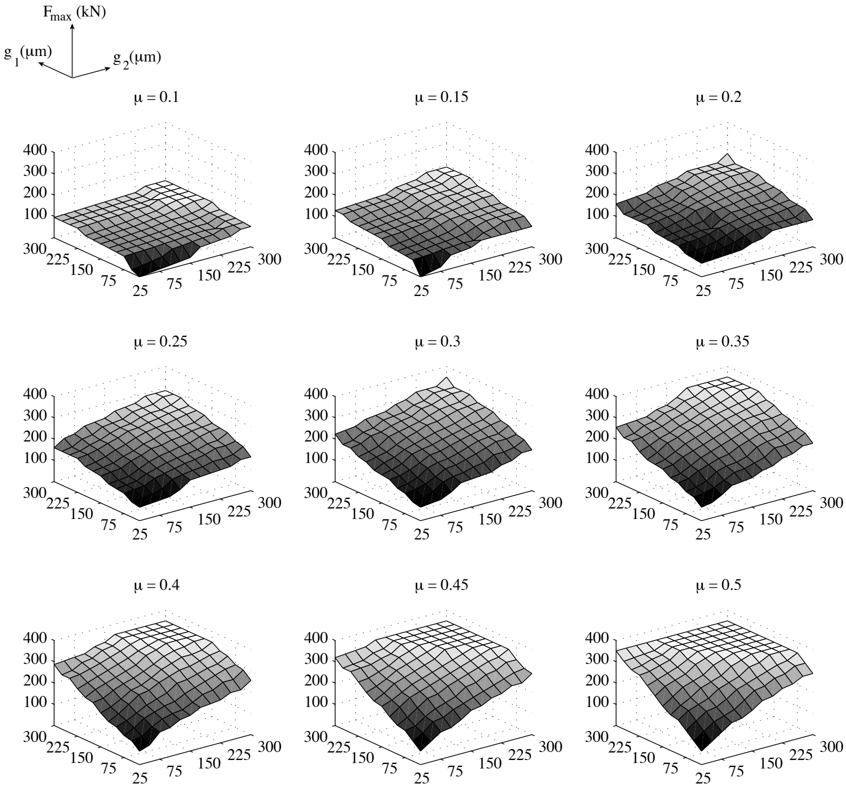

Fig. 4. Summarized presentation of all the results

	ABAQUS	LATIN
Time steps	72	11
Slip tolerance (mm)	1e-4	0
CPU Time (mn)	374	38.1
Wall Clock Time (mn)	407	40

Table 1
Comparison with Abaqus

Wall Clock Time	h	days
ABAQUS direct	8 791	366
LATIN direct	864	36
LATIN mutiple solution	168	7

Table 2
Computational costs - 1296 computations