A non-intrusive global/local cycle-jumping techniques: application to visco-plastic structures

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I've had the privilege to interact closely with Peter Wriggers for fifteen years or so, as for the IRTG 1627 [11]. I now have the great pleasure and honor to work with him on exciting projects, for example on the Virtual Element Method. I am every year more impressed by the depth and breadth of his research, but also by his avant-gardiste winning choices as investing in tools like AceGen. Peter is a gentleman and a very close friend. I hope to have the chance to continue working with him, it is such a pleasure! — O. Allix.

Abstract This paper is a first attempt to make possible the computation of the cycling response of a complex elastoviscoplastic structure up to its possible limit cycle. For this, we try to couple the non-invasive global/local iterative coupling technique [8] with the cycle-jumping method [16]. The different issues regarding the method are discussed on the basis of a 2D examples.

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1 Introduction

In order to correct the drawbacks of the submodeling technique while keeping its simplicity and flexibility, a non-invasive method was proposed which allows exact *local/global* analysis while making use of the same basic tools inside an iterative procedure [8]. It was extended in several directions, notably in [15, 10, 7, 9, 14]. Safran Aircraft Engines was interested in exploring its potential for the detailed analysis of complex structures undergoing viscoplastic strains that can spread over the whole structure.

The quality of the integration of viscoplastic models is very sensitive to the time step. The global and local models do not need the same type steps to achieve the same precision. To handle this issue, we proposed in [2] a space/time global/local non-invasive coupling strategy that we try to extend to cycle-jumping.

For the class of material that we study, one may observe locally accommodation (elastic response around the hardened position), adaptation (stable viscoplastic cycle), or even ratcheting (the viscoplastic cycle evolves continuously). In general, the structure experiences large variations during the firsts cycles, with potentially strong stress redistribution. After that, the evolution is much smoother. The principle to reduce the computational cost is, after the first cycles, to extrapolate the response of the structure over a certain number of cycles [16, 6]. As such, the technique has the potential for high efficiency but depends strongly on the choice of the criteria to decide the number of cycles which can be skipped. In [4, 1] such drawback is alleviated by controlling the time interpolation using the Latin Method but the latter is quite intrusive.

The paper is organized as follows. In Section 2, the constitutive law, the structural example and the reference model are presented. The main lines of the proposed cycle-jumping method are given in Section 3. The principle of the coupling with the two-scale in time and space global/local approach is discussed and illustrated in Section 4. Conclusion and perspectives are provided in Section 5 on the basis of the cycle-jumping procedure applied to a 3D example.

2 Reference problem and solution

The material model used is the one proposed in [13], adapted from the Marquis-Chaboche's behavior [3].The elasticity itself is linear and isotropic. The nonlinear part of the model is ruled by the yield function based on von Mises criterion. The plastic strain tensor ϵ^p is split into a fast part (f) and a slow part (s) with the associated values of the cumulated plasticity p as follows:

$$\dot{\epsilon}^p = \dot{\epsilon}^p_f + \dot{\epsilon}^p_s \quad and \quad p_i = \int_0^t \sqrt{\frac{3}{2}\dot{\epsilon}^p_i : \dot{\epsilon}^p_i}\, d\tau \quad \text{with for } i \in \{f, s\} \tag{1}$$

The kinematic hardening $X = X_f$ is only related to the fast cumulated plasticity and follows an Armstrong-Frederick's formulation. The fast plasticity dominates for strain rates in the range $\left[10^{-5},\ 10^{-2}\right] s^{-1}$ whereas the slow one dominates in the range $\left[10^{-9},\ 10^{-5}\right] s^{-1}$. The material of interest being confidential, we make use of the parameters given in [12] for a nickel based superalloy IN100 evolving at 800°C which is the mean temperature value during a flight.

In order to precisely assess the lifespan of the structure, a damage criterion should be added as in [17]. The 2D example of Figure 1 is used in the paper.

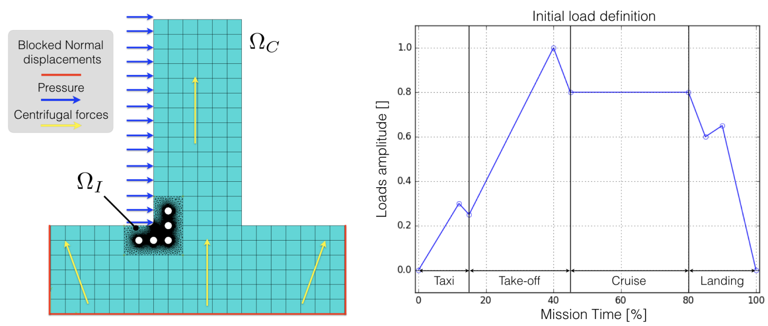

Fig. 1: Monolithic approach: reference model and definition of one cycle.

The problem outlines a turbine blade. The external loads (pressure, temperature, centrifugal force) evolve in time according to the curve of Figure 1 which mimics the main phases experienced by an engine during a flight. Asymptotic elastic behaviors like perfect elasticity or accommodation lead to high-cycle fatigue whereas plastic shakedown (adaptation) or ratcheting conduct to low-cycle fatigue.

The example of this paper corresponds to fatigue with adaptation because the viscous effects due to large plasticity dominate the response at the considered high temperature regime. As a first approximation, we consider that the structure is stabilized when the maxima of both total plastic strain and displacement increments are respectively below 10^{-6} and 10^{-5}, which occurs at about 150 cycles in this example.

3 Summary of the chosen cycle-jumping technique

In what follows, $Y_i(c)$ denotes the value of the internal variable Y_i at the end of cycle number c, $Y_i'(c) = Y_i(c) - Y_i(c-1)$ approximates its "derivative" and $Y_i''(c) = Y_i'(c) - Y_i'(c-1)$ its "second derivative".

In this section, we try to summarize the chosen cycle-jumping technique which is adapted from [5]. Note that the straight procedure as described in that paper fails in our examples, which stresses the difficulty of setting a proper cycle-jumping procedure:

1. The first aspect is the choice of a pertinent internal variable, or set of internal variables, to estimate the number of cycles Δc which can be skipped. In our case, it appears that the best choice is the fast cumulated plasticity p_f computed at the end of cycles (the evolution of this quantity constitutes the shakedown curve as shown in Figure 2).
2. At any stage of the process, the computation of the possible jump is made after the full computation of three cycles. To compute the jump Δc, one first eliminates the Gauss points that are stabilized, that is for which $p''_f < 10^{-12}$. The remaining set of Gauss points is denoted by GP. The chosen value is then $\Delta c = q_{Extr} Mean_{GP} \left\lfloor \frac{p'_f[c]}{p''_f[c]} \right\rfloor$.
3. The quality factor q_{Extr} is computed once for all from the previous formulae by forcing a first jump of fixed length $\Delta c = 2$ after the first three cycles.
4. To extrapolate the whole set of internal variables, we consider a first approximation, denoted $\tilde{Y}'_i$, of the slope after the jump of any internal variable $\tilde{Y}'_i \cong Y'_i(c) + Y''_i(c)\Delta c$. The slope used to extrapolate Y_i is defined as $0.7Y'_i + 0.3\tilde{Y}'_i$ that is $Y_i(c + \Delta c) \equiv Y_i(c) + (0.7Y'_i + 0.3\tilde{Y}'_i)\Delta c$.
5. After the jump, one computation is needed to rebalance the structure starting from the extrapolated values of the set of internal variables, before computing the next three cycles.

Figure 2 illustrates the first three aspects of the process.

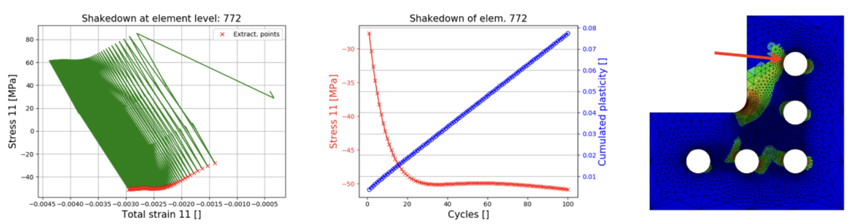

Fig. 2: The values at the end of cycles (left, red dots), constitute the shakedown curve (middle), for the selected Gauss point (right).

4 Coupling with the global/local method

The nonlinear global/local non-invasive coupling proposed in [2] is used in order to insert structural details given by local models into the global coarse representation of the whole structure, see Figure 1. Thanks to an iterative coupling the solution obtained by the separate models converges toward the reference. In order to improve the performance, as explained in the introduction, the solutions are weakly coupled in time: the synchronization only occurs at the time steps necessary for the global model, see [2] for more details.

The quality of the integration of viscoplastic models is very sensitive to the size of the time steps. The global and local models do not need the same type steps to achieve the same precision regarding the integration. Moreover, if one does not achieve a compatible precision between the two models, the local-global procedure may not converge to the reference. To handle this problem, we proposed and compared in [2] various space/time global/local non-invasive coupling strategies. The most efficient one, called weak time-coupling, which allowed us to achieve the desired precision, is schematized in Figure 3.

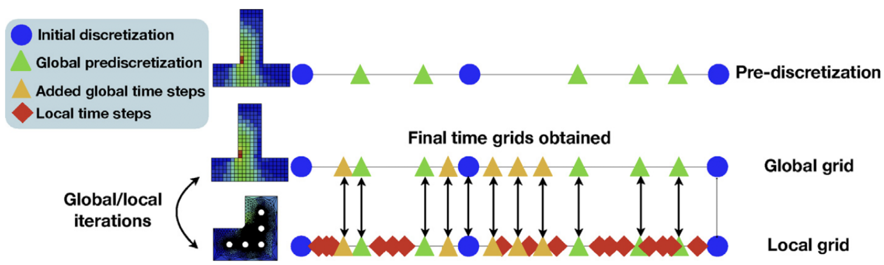

Fig. 3: Schematization of the weak-time coupling strategy

After the computation of three consecutive cycles by the previous coupling algorithm, the question is which model to choose for the estimation of the jump length. The critical areas being located in the local model, a common skipped length, computed on the local model, is used in the global and local models. Then the extrapolation strategy is applied to the global and local models and the weak coupling is applied for the next 3 cycles. Figure 4 summarizes the gain obtained with the cycle-jumping procedure with about 40 cycles computed over the 150 cycles simulated.

Figures 5 and 6 compare the von Mises stress and the cumulated plasticity at the last cycle for the reference and cycle-jumping procedures. The maximum relative errors are respectively about 2% and 0.4% compared to a fine monolithic computation. Note that the computation is never stopped just after a jump, but after few normal cycle computations in order to let plastic redistribution smooth the solution.

5 Conclusion

Our experience of cycle-jumping is that it is still an art to define a proper procedure. Maybe this is due to the severity of the chosen example which reaches nearly perfect

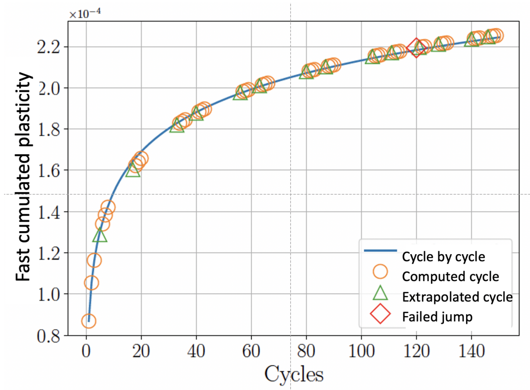

Fig. 4: Overall view of the computed and skipped cycles.

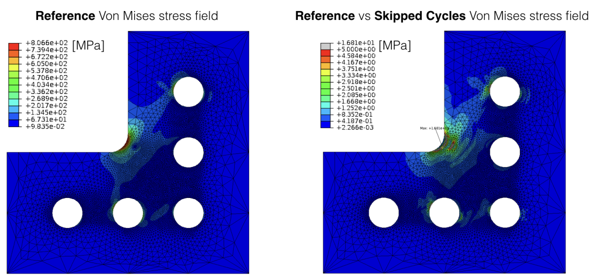

Fig. 5: Accuracy obtained with the cycle-jumping method: von Mises stress.

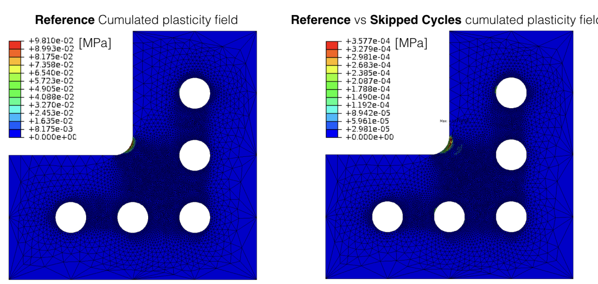

Fig. 6: Accuracy obtained with the cycle-jumping method: total cumulated plasticity.

viscoplasticity on some critical areas of the structure. For too large jumps or not precise enough extrapolations, rebalance may not even be possible. Our proposed procedure leads to satisfactory results in terms of precision even if the factor of 4 for the gain that we obtained is not as high as what can be observed on examples from the literature about plasticity.

Let us note that it seems that 2D cases are more severe than 3D cases. This may be due to the fact that in 3D examples, a whole section never fully evolves in a plastic manner. This is at least what appears from our first experiments concerning the application of the proposed cycle-jumping procedure on a global 3D example of 1.510^6 degrees of freedom over 50 cycles (see Figure 7). In this example, the exact same procedure as the one defined in section 3 was applied.

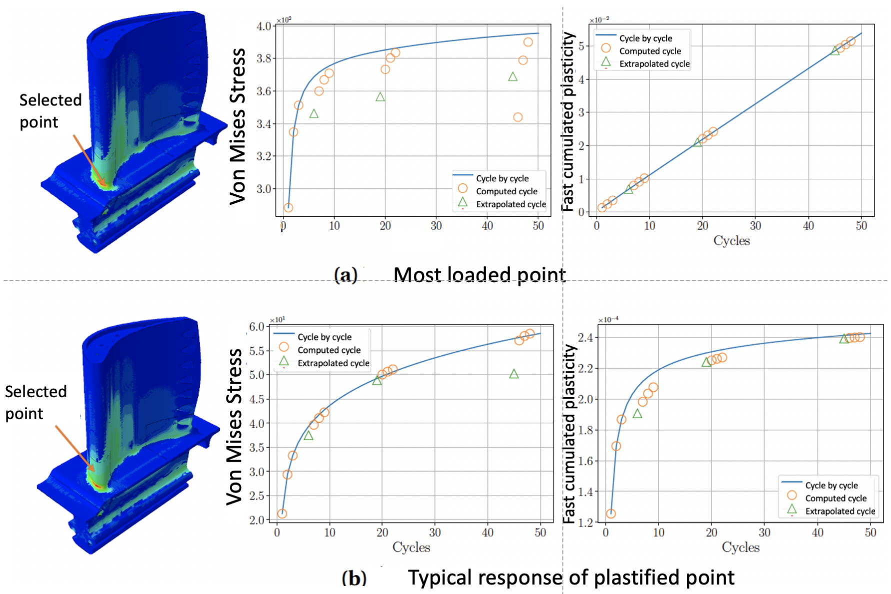

Fig. 7: Application of the proposed cycle-jumping procedure to a 3D global model.

What is still lacking, and which would probably imply a more intrusive procedure, is to include an evaluation of the quality of the solution within the process.

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