Efficient thermo-mechanical modelling of cyclic loading with Chaboche type constitutive law coupled with damage

Laurent Duchêne[1], Hélène Morch[1], Carlos Rojas-Ulloa[1], Víctor Tuninetti[2] and Anne Marie Habraken[1]

[1] ArGEnCo department, University of Liège, Belgium
[2] Department of Mechanical Engineering, University of La Frontera, Chile
l.duchene@uliege.be

Abstract. This paper describes a numerical modelling approach to study the behaviour of a solar receiver tube subjected to cyclic thermomechanical loading. The Lagamine finite element (FE) code was utilized along with a Chaboche type material law and a Lemaitre's unified damage model to simulate the material behaviour under fatigue, creep, and corrosion. The cycle jump procedure is evaluated, as it is a method for efficient computation of long-term evolution of material behaviour under cyclic loading. The procedure involves computing a number of cycles in the FE code, then extrapolating the results from these cycles over a number of cycles. This alternating process is repeated until the end of the computation. A parametric study was achieved to assess the effects of different strategies within the cycle jump. It was observed that the strong evolution of the material behaviour for the first cycles (around 100 cycles) of the computation prevented the use of the cycle jump during that period. Also, a sufficient number of cycles (minimum 4) must be computed with the FE code between the jumps to ensure reaching a stable solution. With the optimum parameters, the cycle jump permitted to significantly decrease the computation time (factor 10), while having a limited impact on the accuracy of the results (lower than 1%).

Keywords: FEM, Cyclic loading, Damage, Cycle jump.

Introduction

In various industrial applications, an increased efficiency of the key components can be reached if the engineers take profit of the plastic regime of the constituent materials. However, this enhanced exploitation of the material can be detrimental for its lifetime. In this respect, advanced modelling can be used to reliably find the optimum balance between material lifetime and efficiency.

In this study, a Chaboche-type thermo-mechanical constitutive law [1-2] was implemented in Lagamine finite element (FE) code (in-house software, MSM team, ULiège), whose material parameters were identified from a comprehensive experi-

mental campaign. This constitutive model was coupled with a multi-physics damage model in order to predict the degradation of the material due to creep, fatigue and corrosion. The parameters of the damage model were also derived from experimental tests.

The largely non-linear and history dependent characteristics of such law impose to apply the loading incrementally with sufficiently small time steps. This procedure can be highly CPU time consuming in case of cyclic loadings, where each cycle must be actually modelled with numerous time increments. However, in such cases, it can be expected that successive cycles will lead to similar evolutions of the variables of the model. We can profit from these similarities to avoid the full computation of all cycles. The cycle jump procedure [3] consists in fully computing a few cycles with the FE model; then, the evolution of the variables of the model is extrapolated over some cycles. A particular attention must be paid to the damage variables which are used to track the degradation of the material during the successive cycles.

This paper assesses the effects on the accuracy of the results and on the computation time of the strategy of the cycle jump procedure, in terms of the number of fully computed cycles, number of jumped cycles, selection of variables to extrapolate, and extrapolation scheme.

1 Description of the numerical model

1.1 Chaboche constitutive law

The Lagamine FE code utilized in this study incorporates a Chaboche type material law that was initially developed by [4] and is based on the Chaboche viscoplastic constitutive model framework [5]. The model involves decomposing the total strain into thermal, elastic and plastic strains. The stress and elastic strain are related through Hooke's law, while the yield locus is defined using the von Mises criterion. The evolution of the isotropic hardening variable is defined by a rate type equation that takes into account the accumulated plastic strain. The kinematic hardening related variable is expressed as the sum of three back-stresses that accurately model its short term and long term evolution during cyclic loading. The evolution of the three back-stresses is based on the nonlinear kinematic hardening rule of Armstrong-Frederick, with additional terms to take into account the effects of temperature variation and static recovery.

As proposed by [4], the cyclic hardening is modelled in the kinematic hardening rule through the evolution of the dynamic recovery parameter, which evolves from its initial value to a saturated value with a rate type formulation, and changes the amplitude of variation of the back-stress. In this study, to model cyclic hardening, the variation of the dynamic recovery parameter is applied to two back-stresses, to account for the short-term and long-term effects separately.

Overall, the constitutive model provides a comprehensive understanding of the material behaviour in various temperature ranges and loading conditions, and the Lagamine code enables accurate simulation and analysis of this behaviour.

1.2 Damage model

In order to account for the degradation of the material, the constitutive model was complemented by a Lemaitre's unified damage model. In this model, the state of the material is represented by a scalar variable D, which varies between 0 (no damage) and 1 (rupture). However, in this work, the value of D is limited to a critical damage value $D_{crit} < 1$ that would correspond to the appearance of a mesoscopic crack.

At a microscopic level, D can be seen as an image of the concentration of voids in the material. An effective stress can be defined by dividing the actual stress by (1-D), which can be understood as the stress that would exist in an equivalent undamaged material submitted to the same strain. This study will be limited to isotropic damage represented by a scalar form of D, but a more general anisotropic damage can be defined with a tensorial form of D.

To model accurately the evolution of D considering various sources of damage, the proposed approach separates the damage caused by fatigue, creep and corrosion into three distinct components D_f, D_c and D_u respectively, where the total damage is $D = D_f + D_c + D_u$. Each damage component has its own evolution equation adapted to the associated physical phenomena. Experimental observations show that the creep and fatigue phenomena can interact and enhance one another. In this respect, the coupling between creep and fatigue damages is included through the use of the effective stress in their evolution equations. Further details about these evolution equations can be found in [6].

The proposed model is expected to provide an accurate representation of the damage caused by fatigue, creep and corrosion.

1.3 Studied Application

The studied application is a tube from a solar receiver, from which only a section is modelled to limit the computation time (see Figure 1). The tube contains a heat transfer fluid with a temperature of 565°C and it is exposed to a solar flux of 890 kW/m² on its front. The back of the tube is fixed, so that it remains straight. In the model, both faces of the tube slice are kept parallel during the simulation to represent the straightness of the entire tube. To account for symmetry, only half of the tube is modelled, which is meshed with 300 elements, with one element along the axial length (the thickness of the slice), three along the thickness, and 100 along the circumference.

To simulate the daily heating and cooling of the solar receiver, the thermal loading is applied cyclically. At the beginning of the cycle, no solar flux is applied. The solar flux then increases linearly over a period of one hour until it reaches the value of 890 kW/m². The solar flux is maintained for 11 hours (day) before decreasing back to zero in an hour. Finally, the tube is left with no thermal loading for 11 hours (night).

To evaluate the performance of the cycle jump approach, a total of 5000 cycles are simulated.

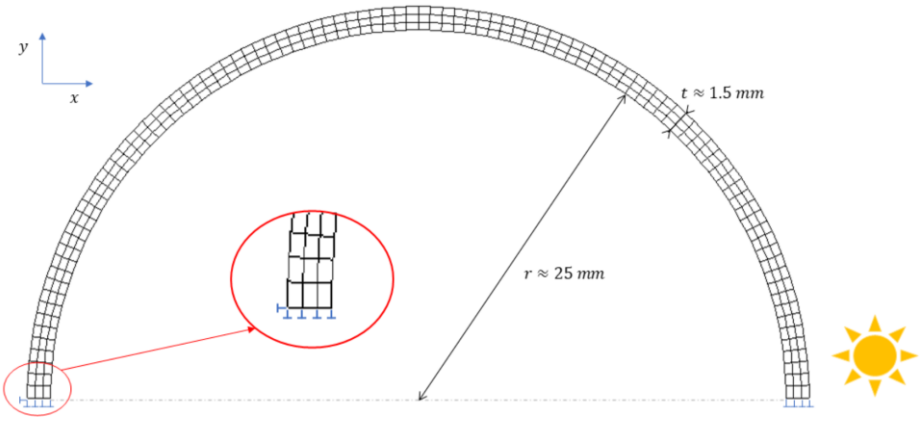

Fig. 1. Boundary conditions, mesh and loading of the half tube (from [6]).

2 Cycle jump approach

The cycle jump procedure permits efficient computation of the long-term evolution of the material behaviour under cyclic loading. The procedure consists of computing a number of cycles, N_i, in the FE code, and then extrapolating the results from these N_i cycles over a number of cycles, N_j. The FE simulation is then restarted from cycle $N_i + N_j$ and the process is repeated until the end of the computation (see Figure 2). The cycle jump is expected to decrease the computation time, while having a limited impact on the accuracy of the results, in terms of stresses, damage... As detailed in Figure 3, the cycle jump was implemented using a Fortran extrapolator (in blue in Figure 3), and a Python script (in green), the latter being in charge of executing Lagamine FE code.

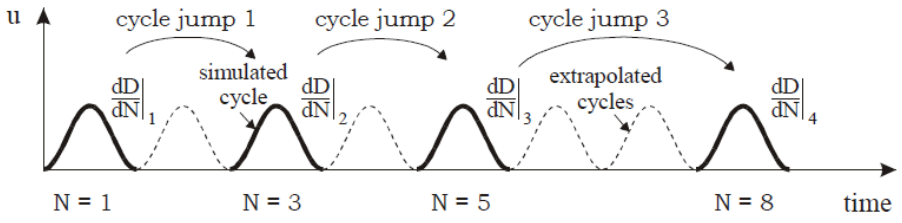

Fig. 2. Cycle jump approach (from [3]).

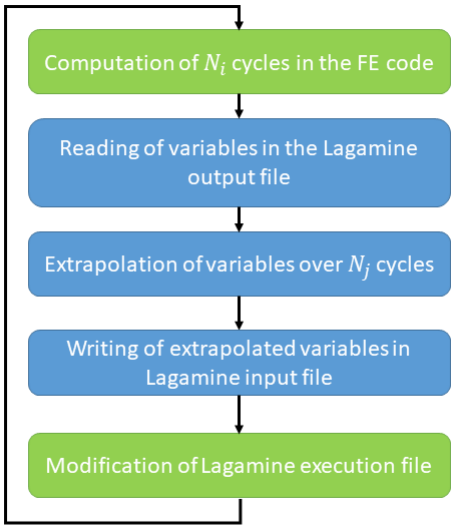

Fig. 3. Flowchart of the cycle jump implemented in Lagamine (from [6]).

The simplest way to perform the extrapolation of the variables is to use a linear extrapolation from the results of the last two computed cycles, among the N_i computed cycles. However, it was anticipated that small numerical errors between two consecutive computed cycles could occur, which would lead to significant errors if these cycles are used for the extrapolation. To prevent this phenomenon, an advanced extrapolation method was developed, where the increment of the variables is calculated over the m last computed cycles using the least square method, with $2 < m \leq N_i$.

Obviously, the values of N_i and N_j are critical in the cycle jump approach and must result from a compromise between accuracy and sufficient gain in computation time. For instance, a sufficient number of computed cycles N_i are necessary to recover a stable FE computation after an extrapolation. Concerning the choice of N_j, three options were investigated: (i) a user-defined constant value of N_j; (ii) idem with different values for different parts of the simulation; and (iii) N_j is adjusted by the extrapolation code from values of selected variables. A classical choice for the latter option is to adjust N_j such that the increment of total damage over the N_j jumped cycles remains below a user-defined threshold [3].

Moreover, not all the variables of the FE code need to be extrapolated. For instance, the variables that are known to be identical at every cycle, or the variables that can be easily computed from others by the FE code at the restart can be advantageously removed from the extrapolation procedure. Nonetheless, such fine tuning of the approach requires a good knowledge of the physical phenomena at play during the simulations.

The effects of the parameters of the cycle jump approach as well as the various options described above are evaluated in the next section.

3 Results

As the Chaboche constitutive law includes creep and relaxation effects, the material behaviour progressively evolves during the loading, with significantly higher rates for the first cycles. Indeed, Figure 4 shows the evolution of the axial stress in the critical element of the tube during the first 100 cycles, this element being located in the front of the tube, with the highest solar flux. The short-term evolution of the stress during one cycle cannot be distinguished in the figure, but the envelope of minimum (at day time) and maximum (at night time) stresses is visible. The evolution of the envelope curves stabilizes after around 50 to 100 cycles. In order to obtain accurate results with the cycle jump approach, it is important to avoid its activation during this period of rapid material evolution. It was therefore decided, for this application, to start the jumps after cycle number 100, the full FE computation being always used before.

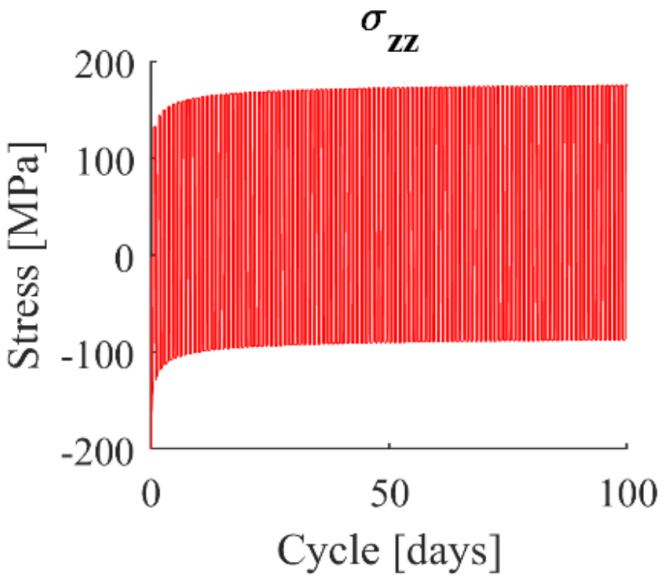

Fig. 4. Axial stress evolution, full FE computation (from [6]).

3.1 Influence of N_j

As explained in Section 2, different options were developed for the selection of the optimum value of N_j throughout the computation: constant, constant by blocks and automatic. Figures 5 and 6 show the effects of two options on the computation of the accumulated plastic strain and the total damage in the critical element.

The two options are:

- N_j by blocks: the value is fixed depending on the considered cycle as
  - N_j =16 for cycles 100 to 500
    (cycle jump not activated for the 100 first cycles)
  - N_j =26 for cycles 501 to 2000
  - N_j =36 for cycles after 2001
- N_j auto: the value is automatically computed by the cycle jump code such that the increment of total damage on the jumped cycles is limited to 5.10^{-4} for all the elements of the FE mesh.

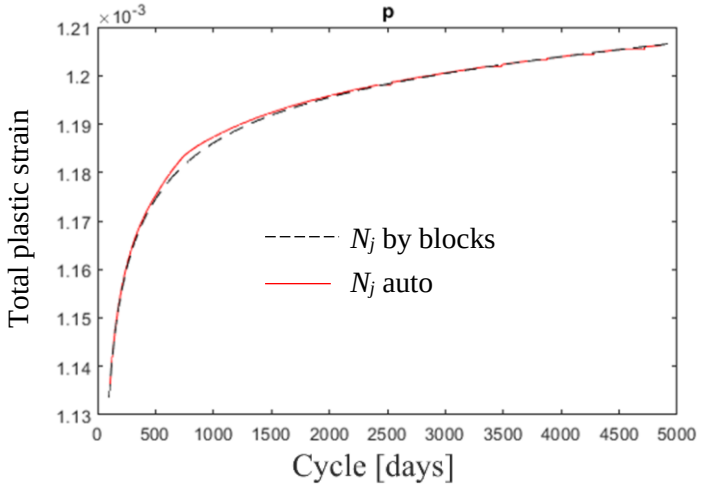

Fig. 5. Evolution of the cumulated plastic strain, effect of N_j.

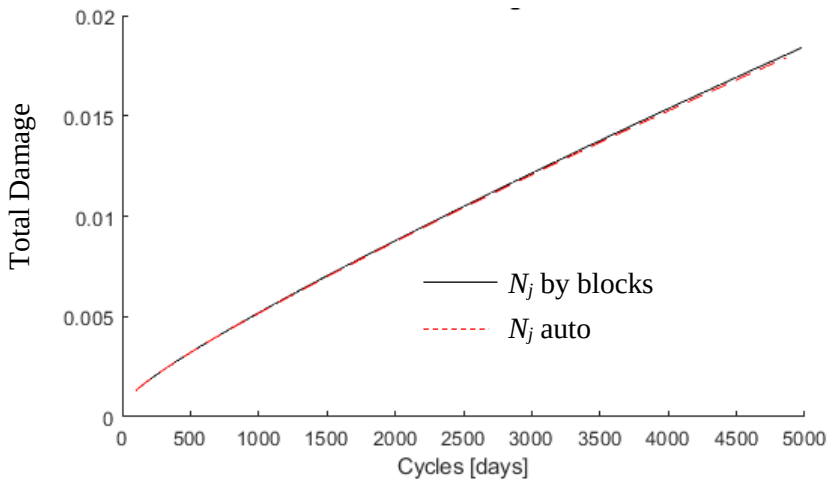

Fig. 6. Evolution of the total damage, effect of N_j.

Note that the option of constant N_j for the whole simulation was not tested here as it was expected to be inefficient. Indeed, using a small value, e.g. 16 throughout the simulation would yield to larger CPU time compared to the N_j by block option, while a high value, e.g. 36 would lead to less accurate results.

Figures 5 and 6 indicate that the two selected options provide very similar results, and should both be considered acceptable in terms of accuracy. The selection of the best option should therefore rely on the gain in terms of computation time. Figure 7 shows the evolution of the value of N_j during the computation. For the constant value by blocks, the curve simply reproduces the imposed values; for the automatic option, the number of jumped cycles leading to a fixed increment of total damage continuously increased during the computation. This observation is in agreement with the rapid evolution of the material behaviour at the beginning of the computation presented in Figure 4. The values of N_j for both options are very similar at the beginning of the computation, which confirms the adequacy of the chosen value of 16 for cycles 100 to 500. However, the value of N_j increases up to 140 with the automatic computation compared to 36 for the option with blocks, which permits to enhance the efficiency of the cycle jump approach. Indeed, the number of cycles that were actually computed by the FE code is 580 for the N_j by blocks option among the total of 5000 cycles (with 145 jumps), while it is 220 for the N_j auto option (with 55 jumps).

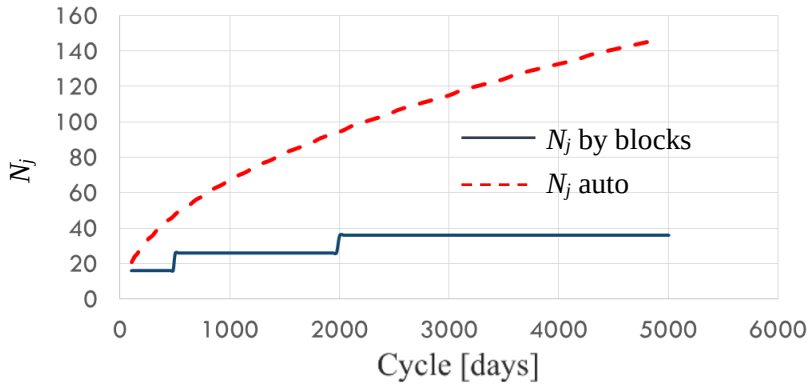

Fig. 7. Evolution of the number of jumped cycles N_j.

3.2 Influence of N_i

Once the best option for N_j is selected (automatic computation based on the increment of total damage), the choice of the value for N_i must be defined. Figure 8 presents the evolution of the total plastic strain as a function of the number of cycles for different values of N_i, i.e. 2, 3 and 4, which remained constant throughout the computation. For these results, the automatic calculation of N_j was selected.

At the beginning of the computation (cycles 100 to ~400), all the results are identical. However, strong differences then appear for N_i = 2, which indicate that a wrong extrapolation took place during a jump. This error could not be corrected during the computation of the subsequent cycles; on the contrary, it was amplified. For N_i = 3, a wrong extrapolation also took place around cycle 500, which could be corrected and an accurate solution was anyway recovered.

These results indicate that it is important to achieve the extrapolation of the cycle jump approach on a sound basis, which requires the computation of a few cycles by the FE code. For this application, 4 cycles are sufficient to keep the solution stable between the successive jumps.

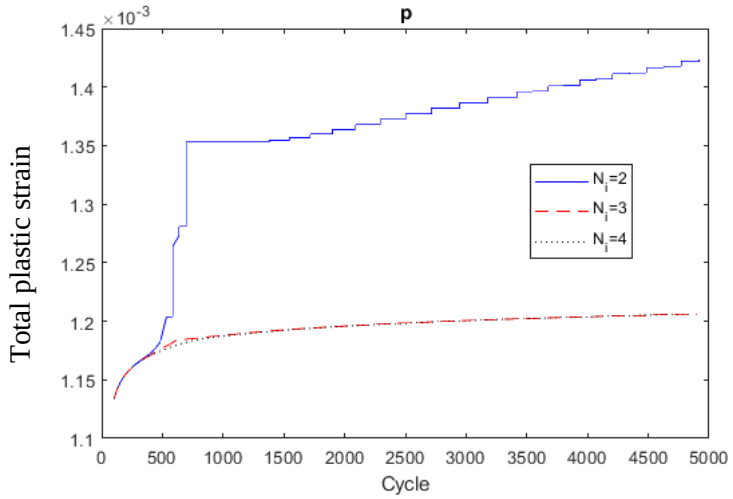

Fig. 8. Evolution of the cumulated plastic strain, effect of N_i.

3.3 Influence of the extrapolation technique

For the application in this paper, the linear extrapolation based on the two last FE computed cycles and the least square method from the m last cycles ($2 < m \leq N_i$) showed almost identical results (not shown here). Actually, if N_i = 2, these two methods become identical; and if N_i is larger, the solution is sufficiently stable, so that the linear extrapolation based on two cycles is accurate enough.

However, if the FE computation is likely to produce oscillations, which would be detrimental in the computation of the extrapolated values, the least square method can enhance the stability of the extrapolation.

Similarly, the comparison of the results obtained by extrapolating all the variables of the FE computation or a reduced set of variables showed very limited effects.

3.4 Optimal values of the cycle jump parameters

Based on the parametric study of the previous sections, the following optimal values were selected in order to reach a good accuracy of the cycle jump approach, while allowing a significant gain of computation time:

- The first 100 cycles are computed with the full FE code;
- $N_i = 4$;
- N_j is automatically computed to limit the increment of damage to 5.10^{-4};
- The extrapolation is based on the two last computed cycles;
- All the variables of the FE code are extrapolated.

Figures 9 and 10 show the comparison between the full FE computation and the cycle jump approach in terms of axial stress and total damage respectively. In these figures, both results are almost superimposed, proving the accuracy of the cycle jump. Actually, the error on the total damage is 0.85% at cycle 5000.

Moreover, the efficiency of the approach is substantial as the computation time reduced from 104 hours for the full FE simulation to 11 hours for the cycle jump, including the first 100 cycles.

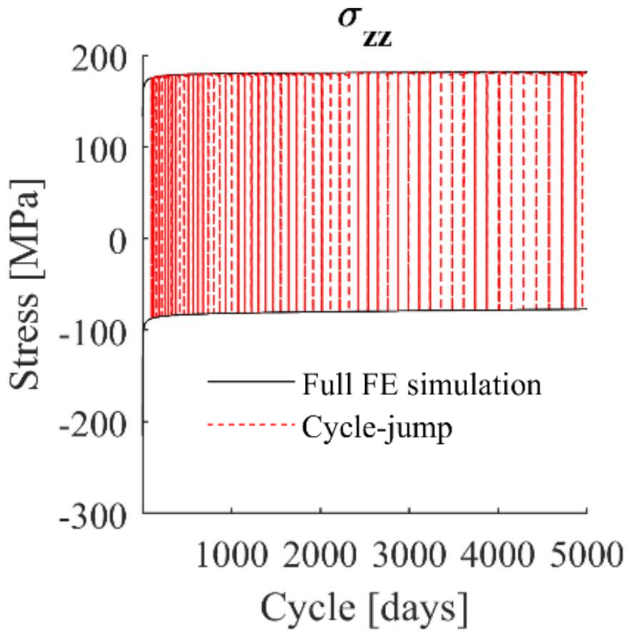

Fig. 9. Axial stress evolution, comparison between full FE computation and simulation with cycle jump (from [6]).

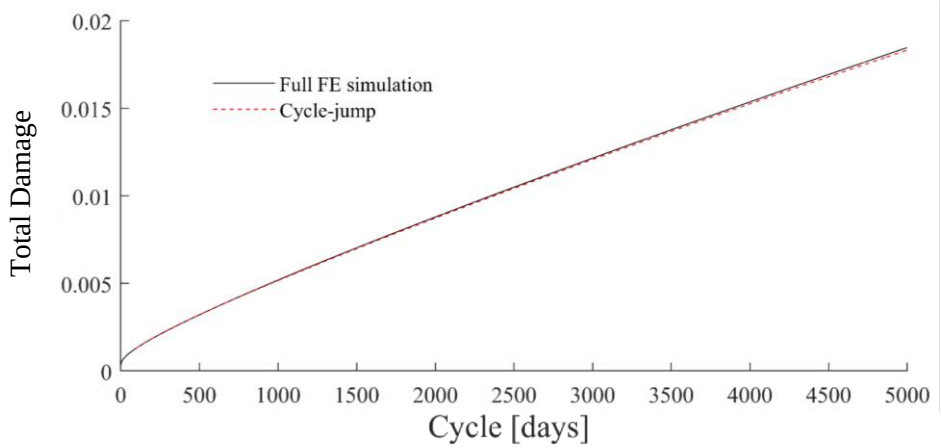

Fig. 10. Evolution of total damage, comparison between full FE computation and simulation with cycle jump (from [6]).

4 Conclusions

This paper presents the application of the cycle jump approach to improve the efficiency of a complex FE computation including the following features:

- Chaboche type elasto-visco-plastic constitutive law;
- Multiple back-stresses;
- Cyclic hardening effects;
- Creep, fatigue and corrosion damages;
- Cyclic loading up to 5000 cycles.

A parametric study permitted to derive the optimal values for the key parameters of the cycle jump approach, which are detailed at the beginning of section 3.4. It must be emphasized that these values are valid for the application of this paper. They certainly need to be adjusted if other applications are targeted.

Finally, it is shown that the cycle jump approach permitted to obtain very accurate results (error lower than 1%) with a significant gain in computation time (reduction by a factor close to 10).

Acknowledgement

The authors are grateful to John Cockerill Energy and to the Walloon Region for its financial support. The authors acknowledge the MecaTech Cluster. A.M. Habraken acknowledges the Belgian Fund for Scientific Research FRS-FNRS for its support.

References

1. Morch H, Duchêne L, Harzallah R, Tuninetti V, Habraken AM (2021) Efficient temperature dependence of parameters for thermo-mechanical finite element modeling of alloy 230. European Journal of Mechanics - A/Solids 85: 104116. https://doi.org/10.1016/j.euromechsol.2020.104116.
2. Ahmed R (2013) Constitutive Modeling for Very High Temperature Thermo-Mechanical Fatigue Responses. Ph.D. Thesis, North Carolina State University.
3. Van Paepegem W, Degrieck J, De Baets P (2001) Finite element approach for modelling fatigue damage in fibre-reinforced composite materials. Compos. Part B Eng. 32(7): 575–588, doi: 10.1016/S1359-8368(01)00038-5.
4. Ahmed R, Hassan T (2017) Constitutive modeling for thermo-mechanical low-cycle fatigue-creep stress-strain responses of Haynes 230. Int. J. Solids Struct. 126–127, 122–139, https://doi.org/10.1016/j.ijsolstr.2017.07.031
5. Chaboche JL (2008) A review of some plasticity and viscoplasticity constitutive theories. Int. J. Plast. 24, 1642–1693, https://doi.org/10.1016/j.ijplas.2008.03.009
6. Morch H (2022) Thermomechanical modelling of the creep-fatigue behaviour and damage of Nickel-alloy receiver tubes used in Concentrated Solar Power plants. Ph.D. Thesis, University of Liège. Available from: https://hdl.handle.net/2268/295588