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A mixed time integration scheme for virtual fabrication of steel plate girders

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ABSTRACT

In this paper the use of mixed time integration is proposed to increase the efficiency of welding simulation. A technique similar to the one commonly used in sheet metal forming is applied to the welding of steel plates. The welding procedure can be divided into two very distinguishable parts with significantly different characteristics. The first part, the phase of the actual welding, is a fast paced, rapidly changing process that involves highly nonlinear material behavior. The second part, the phase of cooling down, is a slow paced, slowly changing process that does not result in dramatic changes in the material behavior. In this project, explicit time integration was used for the thermo-mechanical analysis of welding and implicit time integration was proposed for the subsequent cooling phase. This paper presents examples based on the conventional fully implicit solution and the proposed explicit integration solution using the finite element codes ABAQUS/Standard and ABAQUS/Explicit, respectively.

1. Introduction

In the simulation of sheet metal forming it is common practice to use a combination of explicit and implicit time integration as a result of the special characteristics of the procedure: the first part of the process is stamping which is then followed by a phenomenon called springback. Stamping is a rapid process and involves a high degree of non-linearity and contact. On the other hand springback, which occurs during unloading, is a relatively slow process during which the sheet metal part (the blank) undergoes further dimensional changes arising from the release of elastic strain energy accumulated in it during stamping [1]. Since explicit time integration is more suitable for phenomena such as stamping and implicit time integration is more suitable for phenomena such as springback it seems natural to combine the two and employ them where they perform best. In Section 3 the advantages and disadvantages of both explicit and implicit time integration is discussed in more detail.

The simulation of welding can also be divided into two very distinguishable parts: the welding itself and the cooling down that follows. This is demonstrated in Section 2 using an example studied by the authors previously [2]. After discussing the general characteristics of the two time integration methods in Section 3, special attention is paid to the stability of the explicit method which is conditionally stable and requires a limit on the time step size to remain stable. In Section 4 it is also discussed how this limit can be improved to avoid very computationally costly analysis using a technique called mass scaling. Finally all this is put into practice using three examples to demonstrate the applicability of explicit time integration in a mixed time integration scheme for welding simulations.

By finding the right balance in combining the advantages of explicit and implicit time integration methods the path to utilising virtual fabrication to "manufacture" numerical models for virtual experiments both in research and design is demonstrated. This paper focuses on the applicability of explicit time integration in the simulation of welding comparing it to the more commonly used implicit method. In the final conclusions section a summary of the findings of this research is presented.

2. Background

The main objective of the current research project is to include the simulation of the fabrication process into the design and analysis of welded steel structures. Simulation of the fabrication would allow researchers and engineers to build better numerical models for their structural analyses. Nowadays performance based design is more and more widespread but for building more realistic numerical models that include imperfections the analysts still rely on the recommendations of design codes or other simplified approaches. This is mainly due to the complexity of welding simulation and the very high computational cost that it involves. This work focuses on the development of an efficient numerical analysis technique to calculate the imperfections (residual stresses and distortions) in welded plate girders. In the initial phase of the research [2], in order to identify the main directions of the project, a simple

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example was developed to study the characteristics of welding simulation. A brief summary is given here of the results of this initial study.

In this example an 800 mm long section of steel plate girder with vertical stiffeners on both side of the web is studied as shown in Fig. 1. The web is 600 mm high and 6 mm thick. The flanges are 300 mm wide and 10 mm thick and the stiffeners are 84 mm wide and 6 mm thick. The numbered arrows in Fig. 1 show the sequences and directions of welding (in the example the consecutive sequences are conducted continuously without any break between them). The welding heat source consists of two consecutive nodes held at a temperature of 1500 °C. This heat source moves along the nodes joining the web to the flanges and the stiffeners to the web at the speed of 15 mm/s (a typical welding speed for gas metal arc (GMA) welding [3]).

In Fig. 1 four locations on the girder are marked with numbered dots and Fig. 2 shows the thermal histories of these locations. It has to be noted how rapidly the temperature changes at nodes in the welds (locations 1 and 2). Right after the high temperature heat source passes these nodes their temperature drops significantly.

However, after reaching a relatively low temperature it takes a very long time to cool down further and eventually to reach the ambient temperature (which is not shown in the graph). The other two curves (locations 3 and 4) show that far from the weld the temperature changes are relatively small and after the sharp drop in the other two curves all the four curves remain in the same temperature region.

This example demonstrates how the numerical modeling process of welding can be divided into two clearly distinguishable parts both in space and time. In space: in the welds and in their close vicinity the temperature gradient is very high demanding a high density of finite elements while in the rest of the model a relatively coarse mesh is sufficient. In time: the welding itself is a relatively fast and rapidly changing process while the cooling of the whole structure is a time-consuming and much slower changing process. These special features of welding simulation influence the selection of the numerical methods. During welding and close to the welds the temperatures are changing rapidly in a very wide range and the material behavior is very complex. These characteristics suit the explicit method as discussed in the next section. However, during cooling and far from the welds the temperatures are changing much slower in a narrower range and the material behavior is simpler. These characteristics suit the implicit method. Therefore the efficiency of the numerical simulation can be improved by combining the two methods and applying them when and where they are most efficient.

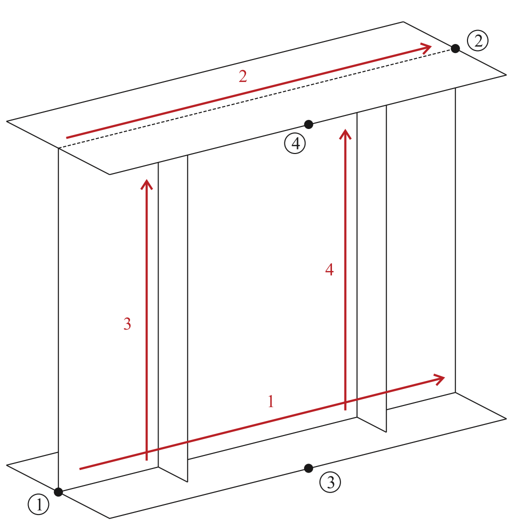

Fig. 1. Plate girder with vertical stiffeners showing the welding sequence 1,2,3,4 and the four points at which the temperature is recorded shown with the point numbers in circles.

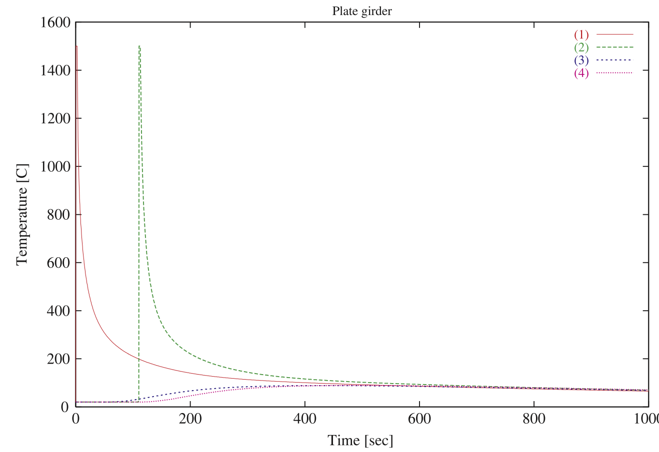

Fig. 2. Temperature history – showing the temperature variations for the four points in Fig. 1.

3. Explicit vs implicit

The fundamental difference between the two time integration techniques is that in explicit methods the unknowns of the equation system can be expressed explicitly therefore there is no need to solve an assembled system of equations. In implicit methods for nonlinear problems the unknowns are present on both sides of the equations therefore the solution of the system of equations must be carefully considered. The main features of explicit and implicit time discretization methods are summarised below.

Characteristics of explicit algorithms:

- computationally more economical per step,
- numerical stability limits the duration of the time steps,
- low memory requirements,
- these methods can more easily handle complex material laws.

The solution of the problem with explicit methods is very straightforward and easy to implement. Since there is no need to solve the system of equations there is also no need to assemble global matrices. This results in a very fast solution of one time step and in very low memory requirements which makes explicit methods very attractive to solve problems with very large numbers of elements. On the other hand the main drawback of the method is its conditional stability. The critical time step can be extremely small which makes the method suitable mainly for rapid phenomena only.

Characteristics of implicit algorithms:

- the computation is more expensive per step,
- larger time steps are possible,
- with a direct solver the memory requirement is large thanks to the large global matrices (an iterative solver can reduce the memory requirement).

Implicit methods can generally handle much greater time steps than explicit methods which makes them more suitable for long-lasting phenomena. On the other hand the solution of one time step is much slower and the larger memory requirements may limit the size of the problem. There are iterative solution methods