Performance-Based Selection of Path-Following Constraints Used for Solving Quasi-Static Problems

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ABSTRACT

In the quasi-static analysis of mechanical and structural engineering problems, it is usually needed to solve a system of nonlinear algebraic equations constructed by the Finite Element methods. Most significantly, the incremental exertion of the loads (defined by the incremental change of a load factor) should be determined in each step of the quasi-static analysis. This is a more critical task when we face limit points (e.g. snap-back or snap-through) in the solution path. A pure Newton-Raphson scheme is not capable of passing these limit points. Therefore, employing path-following methods is recommended to tackle this drawback. The method adds another equation, called a 'constraint', to the equilibrium equations in order to be able to robustly determine the incremental change of the load factor. There are several path-following constraints in the literature each of which has their specific characteristics.

In this paper, we have used two of the most conventional constraints (cylindrical arc-length and dissipated energy control) together with a previously proposed one by the authors (angle control [1]) and two new constraints (kappa and kappa-omega control). For a quantitative comparison of these constraints, we have proposed a set of performance measures based on our definitions of the speed, accuracy, and robustness when solving the problems. The speed is defined as the CPU time (either in total or averaged per step) needed for the calculations of analysis. We defined the maximum absolute value of the residual vector in each step as the accuracy. And, the robustness is simply defined to be the percentage of the length of complete solution path that each constraint helps the solver progress. Furthermore, four performance criteria are defined (by different combinations of the mentioned performance measures) to more conveniently assess the overall as well as instant performance of the constraints. Because there is no constraint outperforming the other ones in all situations of all problems for all desired performances, it is more effective to select the constraint in each step of the analysis. Finally, the best constraint according to a desired performance criterion is automatically chosen and used in each analysis step of the example problems. It should be noticed that all of the mentioned criteria are designed to relatively compare the constraints for selection purposes. In other words, it is assumed that the relative order of performance of the constraints will remain the same when using different hardware, software, or programming style.

The first example problem models a cohesive damage zone by interface elements at the centreline of a perforated beam. Kappa and kappa-omega control outperform the other ones where cylindrical arc-length control misdirects the solution path to the artificial unloading after around 40% progress. In the second example, we have utilized a gradient enhanced damage model for a dog bone shaped beam. The kappa control performs better in terms of overall robustness, speed, and accuracy where dissipated energy and angle control are faster and more robust without considering the accuracy. In addition, the dissipated energy control with fixed incrementation could not converge and stopped the analysis after around 22% progress.

Results show that the new constraints show the capability of being exploited in continuum as well as

discrete crack models with nonlinear material behaviour. Moreover, the employed selection procedure enhances the performance of the nonlinear path-following solver.

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