SEISMIC DAMAGE ANALYSIS OF A LARGE-SCALE CABLE-STAYED STEEL BRIDGE USING PRECISE SHELL MODELS AND SUPERCOMPUTING

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1. INTRODUCTION

Due to the aesthetical and long-spanning advantages, large-scale cable-stayed bridges have been extensively constructed worldwide in the past few decades, of which many locate in earthquake-prone areas like Japan. Since cable-stayed bridges generally constitute a substantial portion of infrastructure wealth and play critical roles in transportation systems, their damage behaviors should be well understood when subjected to extreme disasters like earthquakes. A sufficient understanding of the bridge seismic vulnerability is also the prerequisite for targeted retrofit and maintenance.

To accommodate the long-spanning capacities, cable-stayed bridges are normally constructed with thin-walled stiffened girders and towers to reduce the adverse effect of self-weight. Previously, the seismic analysis of cable-stayed bridges were mainly concentrated on the modelling of geometric nonlinearities from large deformation, cable sag effect, and axial-bending interaction, without much considerations on the material nonlinear stress-strain behaviors of bridge components (Wilson and Gravelle 1991; Tuladhar et al. 1995). For large-scale cable-stayed bridges in seismic regions, the critical bridge components like main towers and stiffened girders are very likely to undergo inelastic responses under super strong earthquakes, which may significantly influence the overall bridge seismic performance. Currently, fiber models composed of nonlinear material fibers are widely used for seismic damage and failure analysis of cable-stayed bridges (Wang et al. 2017). However, fiber models usually integrated into beam elements are unable to capture the local nonlinear behaviors of bridges, such the local buckling of thin-walled main towers or stiffened girders. In most cases, the local buckling of thin-walled members may dominate the structural ultimate failure. Hence, it is essential to utilize more precise models to capture such behaviors for a more accurate prediction of the seismic damage of cable-stayed bridges.

This study uses shell models to replace conventional fiber models to simulate the seismic damage of a large-scale cable-stayed steel bridge in Japan. The high-fidelity shell models of the thin-walled main towers and stiffened girders with massive discretized nodes and elements are established for the prototype bridge. Nonlinear pushover analysis is carried out on the bridge model with the assistance of parallel computing using supercomputer systems to improve the computation efficiency. The Domain Decomposition Method serving as the core algorithm of massive parallel computing is adopted in the current pushover analysis. The analysis results are expected to help reveal a more accurate seismic damage behavior for large-scale cable-stayed bridges.

2. BRIDGE PROTOTYPE AND MODELLING

The considered prototype is a three-span cable-stayed bridge with two diamond-shaped steel main towers. The total length of the continuous bridge stiffened girder is 1000 m, divided by a 500 m-long main span and two side spans with a length of 250 m. The bridge main towers and stiffened girders are made of structural steels with typical thin-walled box sections (Fig. 1). Two different patterns of FE models are established for the bridge prototype, that are nonlinear fiber models and refined shell models. Since the steel main towers and the long-span girders are very susceptible to plastic responses under strong earthquakes, their behaviors are modelled using these nonlinear elements. Fig. 1 shows the sample segments of the stiffened girder and tower shell models. If using conventional fiber models, only two nodes with one element are needed for modelling one segment. For the shell models, however, more than 12000 nodes and 13000 elements are required for a single tower segment, and more than 43000 nodes and 45000 elements for a stiffened girder segment. The significant increase in the numbers of nodes and elements undoubtedly complicates the analysis, requiring stronger processors and longer computation time. The parallel computing using supercomputers will be utilized to conduct the shell model analysis.

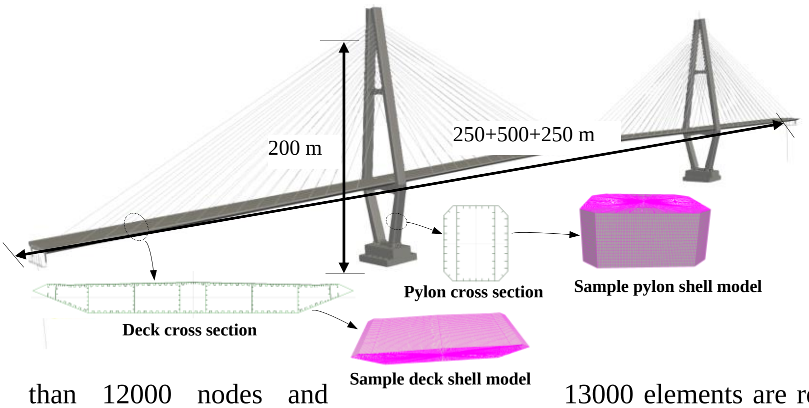

Fig. 1 Basic information for prototype and modelling

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3. BASICS OF DOMAIN DECOMPOSITION METHOD

The Domain Decomposition Method (DDM) (Nikishkov 2007) in the form of sub-structuring has been well suited for large-scale finite element analysis with a remarkable efficiency. Using DDM, a large finite element domain is divided into multiple subdomains with element boundaries. The subdomains analyses are conducted in parallel by separate processors. Necessary connections among subdomains are established through data communications. With load balancing, the DDM is computationally efficient for parallel finite element analysis. The first step for carrying out the DDM is domain partitioning, which partitions the substructure into subdomains and distributes them to specified number of processors. A good domain partitioning should be achieved by fulfilling both the minimization of number of interface nodes and compute load balancing, where graph methods are widely used. After the domain partitioning, both direct and iterative algorithms can be used for the specific finite element analysis. The direct algorithms are simple, capable of predicting computing time and avoiding the convergence problems, whereas the iterative ones are more efficient for large-scale structure problems.

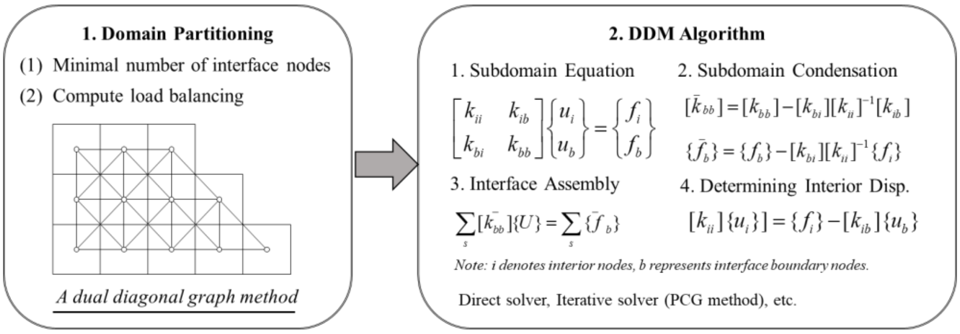

Fig. 2 Basics of Domain Decomposition Method for parallel finite element analysis

4. NONLINEAR PUSHOVER ANALYSIS AND DAMAGE INVESTIGATION

After establishing the refined shell models of the prototype bridge, nonlinear pushover analysis can be carried out with the help of parallel computing using supercomputers. The analysis procedure adopted herein is presented as follows:

(1) Determination of load pattern: first three-directional real earthquake motions are input in the bridge fiber models and time-history analysis is then conducted, from which the maximum seismic responses of the bridge can be obtained. At the occurrence time when the maximum responses are reached, the acceleration response values of the nodes are determined. By multiplying the node mass, the inertial force distribution of the bridge at the time with maximum responses is determined as the load pattern for the pushover analysis on the complicated shell models.

(2) Three-directional pushover analysis is conducted by using the load pattern determined previously. By incrementally increasing the imposed loads, the overall force-displacement curves of the bridge can be obtained. From the pushover curves, critical points indicating different limit states for different components at different locations can be highlighted. The sequence of damage occurrence can also be displayed on the pushover curves.

(3) The same load pattern is also applied in the fiber model for pushover analysis, where the fiber results are used for comparison purposes.

(4) Based on the pushover results, the most vulnerable components/regions with the most probable damage or failure modes under earthquakes can be well identified, which provide sufficient information for targeted retrofit.

5. CONCLUSIONS

In this paper, the seismic damage behaviors of a large-scale cable-stayed steel bridge are investigated using refined shell models with the assistance of supercomputing systems. Although the number of discretized nodes and elements generated by shell models is much more than those of fiber models, the computing efficiency problems of large-scale shell models can be well overcome by using parallel supercomputing. Using the precise shell models, the local yet critical buckling behaviors of the thin-walled members in the bridge can be well captured, which provides a more accurate estimation of the seismic vulnerability of the various bridge components.

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