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A Parallel Finite Element tool in Grasshopper

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Abstract

Parametric techniques provide a sharing platform for multidisciplinary information. Although some structural analysis tools in parametric platform are widespread, these tools rarely have the capability to estimate seismic responses rapidly and accurately. Considering the severe damage caused by strong earthquakes, a parallel finite element analysis tool is implemented as a plugin in the parametric modelling platform—Grasshopper. With the help of the series of components, engineers could achieve static analysis and nonlinear dynamic analysis to any structure. Some open-source codes are incorporated in the program using C++ programming language, which involve matrix calculation libraries, material constitutive models, etc. Two parallel computing strategies, the parallel state transformation procedures (PSTP) and the parallel factorization of Jacobian (PF), are adopted to make up for the low speed of nonlinear dynamic analysis. In Grasshopper, geometries are converted to structural models through nine new data types, i.e. Material, Section, Line Element, Shell Element, Load, Constraint, Analysis, Damping and Model. A case study on two 14-storey frame-shear wall structures with the same parametric modelling logic has demonstrated the operational convenience of the dynamic analysis tool. Variables include geometric variables, topological variables and structural variables. A top displacement time history is presented to show the different seismic performance of these structural models.

Keywords: Parametric technique, Nonlinear dynamic analysis, Parallel computing, Grasshopper plugin.

1. INTRODUCTION

The Sydney Opera House is the first major architecture project accomplished with the help of computation. In the past 30 years, the rapid developing computer technology has gradually changed its own role in the architectural design. Parametric design is a typical creature using the relationship between elements to manipulate and inform the design of complex geometries. The completion of various nonlinear building, e.g. the Heydar Aliyev Center and the Phoenix International Media Center, demonstrates the powerful modelling capability of parametric design. Parametric technique provides a sharing platform for multidisciplinary information. Despite the parametric design is not new to architecture, it is still not very familiar to engineers. Although some structural plugins, like Karamba (2014), are integrated in Grasshopper (2015), a well-known parametric modelling tool, most of them are just used to help structures stand up or explore new forms. There is still a far way to achieve the intelligent structural design, in which all structural components could be distributed automatically, even create new rational structural systems but without negative influence to architectural functions. So far, a lot of researchers have made efforts to this ultimate goal. Combined with the easy-to-control attribute of NURBS surfaces, Li et al (2011) proposed a NURBS-GM method to optimize the strain energy. Huang et al (2006) improved evolutionary structural optimization (ESO) using a bidirectional algorithm, which means that material could be not only deleted but also added to structures during the optimization process. In order to rich the forms of structures, Mueller and Ochsendorf (2015) developed a web-based program named "Structure Fit" to achieve interactive form-finding in the design space. Flager et al (2009) presented a methodology and optimized their structures while considering structure and energy as objectives. Zhang and Mueller (2017) optimized shear wall layouts by utilizing an improved ground structure method. All the algorithms and tools mentioned above only take into account static loads or wind loads into account but no structural safety under earthquakes. Thus, there is a need to develop a seismic analysis tool in parametric platforms.

2. SEISMIC ANALYSIS IN MULTI-OBJECTIVE OPTIMIZATION

In traditional structural design, engineers mostly care about structural safety, but ignore architectural functions and aesthetics, which deeply intensifies the contradiction between architects and engineers. Optimizing buildings is no longer a pure mechanical problem, but a conundrum including multiple professional requirements, e.g. structural rationality, energy saving, and accessibility. That is the multi-objective optimization in the construction industry. To engineers, structural rationality has two basic meanings: make structures stand up and more efficient mechanically. However, just standing up may be sufficient for a sculpture, but definitely cannot satisfy building requirements. In the life cycle of a building, larger earthquakes are possible to happen, which could cause building collapse and some serious secondary disasters, e.g. spreading fire and rock fall in large area. Thus, seismic analysis should be considered in optimization.

Generally, considering the speed of calculation, engineers prefer using equivalent static loads to estimate seismic responses of structures, especially in conceptual design. However, what should be recognized is that the inaccurate approximation could become the source of a wide range of model adjustments in later stage. The trial-and-error design approach still exists in that way.

The nonlinear dynamic analysis is one of the mainstream methods to improve the calculation accuracy, which calculates building responses at discrete time steps using discretized seismic waves. Due to the consideration of material inelastic properties, the calculated results are reasonably more approximate to those during the design earthquake. Nevertheless, the time history method is a double-edged sword, because discretizing time leads to larger workload simultaneously. And to guarantee the architectural diversity, a lot of parametric structural models should be generated. Then the low calculation speed will become the most insurmountable obstacle for nonlinear dynamic analysis to participate in parametric design.

Compared to the two methods mentioned above, the response spectrum method is a compromise method. On one side, standard response spectrums in design codes are statistical results of series of responses under considerable ground motions. So time integration methods are not necessary in this method, which makes it much faster than time history analysis. On the other side, compared to the equivalent static loads methods, the Duhamel integration method for plotting the response spectrums reflects structural dynamic characteristics originally. Thus, it is more appropriate to apply the response spectrum method in the early process of optimization. And the nonlinear dynamic analysis could be used to check the seismic safety of final optimized structural proposals. Due to the space limitation, only the check part is introduced in this paper.

3. PARALLEL COMPUTING IN SEISMIC ANALYSIS

3.1. Basic procedure

The dynamic equilibrium equation of a nonlinear system can be written as follows:

$$m\ddot{v}(t)+c(t)\dot{v}(t)+k(t)v(t)=p(t) \tag{1}$$

where $\ddot{v}$, $\dot{v}$ and v are the vectors of accelerations, velocities and displacements of a structure, respectively; m, c and k are the matrix of mass, damping and stiffness, respectively. The time history analysis involves a time-step-by-time-step evaluation of building response. Thus, the dynamic equilibrium equation is discretized with the i^{th} analytical time step as follows:

$$m\Delta\ddot{v}_i + c_i\Delta\dot{v}_i + k_i\Delta v_i = \Delta p_i \tag{2}$$

Based on the different assumption to the variation of acceleration in an analytical step, the connection among accelerations, velocities and displacements could be established. So, the equation above could be simplified as follows:

$$F\left(\Delta v_i\right) = 0 \tag{3}$$

With the unbalanced force applied, the Newton-Raphson method is adopted to iteratively approximate the solution at the end of each analytical step, which could be expressed as follows:

$$F'\left(\Delta v_i^k\right) \times s_i^k = -F\left(\Delta v_i^k\right) \tag{4}$$

$$\Delta v_i^{k+1} = \Delta v_i^k + s_i^k \tag{5}$$

where the $F'(\Delta v_i^k)$ is the stiffness matrix, also called the Jacobian, and s_i^k is the increment of displacement vector after the kth iteration in the i^{th} analytical time step.
With a short analytical time step, a complete nonlinear dynamic time history analysis usually requires thousands of iterations, especially to skyscrapers and large span spatial structures. Therefore, it is necessary to speed up nonlinear time history analysis.

3.2. Parallel computing and integration

Parallel computing is a type of computation in which many calculations or the execution of processes are carried out simultaneously. Significant computation workload in material-level state determination is satisfied to achieve the accuracy of nonlinear dynamic analysis. To solve this problem, the state transformation procedures (STP) were proposed by He (2017). In the STP, the sections at integration points are classified into three states, i.e. initial state, elastic state and nonlinear state. It should be noted that when strong earthquake comes, a large portion of sections remains in elasticity, which means their stiffness is still kept as initial value. That is the repeated state determination of sections is not necessary until their nonlinearity occurs. Solving nonlinear equation also takes a lot of time in nonlinear dynamic analysis. Considering the sparseness, symmetry and positive definiteness of stiffness matrix, sparse Cholesky factorization method is appropriate to determine the increment of displacement vector during iteration. The STP and sparse Cholesky factorization are combined with parallel computing technique to achieve higher acceleration.

A new parallel finite element program using C++ program language was developed by Fu et al (2015) to achieve the futures mentioned above. Some open-source codes available are integrated into the program. The main matrix operation library includes Eigen (accessed on 2015), CHOLMOD. OpenMP is integrated to balance thread allocation in parallel computing to avoid meaningless thread wait. Concrete02 (1994) and steel02 (1983) are adopted from OpenSees (2000). In terms of shell element, the famous MCFT (1986) is integrated as 2D concrete material. Fiber beam-column element (1996) and layered shell element (2015) are integrated in the program to reflect structural seismic responses in macroscopic level from material properties in microscopic level.

4. STRCUTRUAL DATA TRANSMISSION

The enormous quantity of model data requires fast information conversion from Grasshopper to the program. The repeated calling to "DllImport" function usually causes severe time waste. Moreover, the existing of global variables in the parallel finite element program heaps up the obstacle to control and monitor variables in multi-process computing. Thus, easy text conversion is adopted in the core component. Nine data types are developed to incorporate all the structural information in the parallel finite element program, i.e. Material, Section, Line Element, Shell Element, Load, Constraint, Analysis, Damping and Model. In material component, users could choose concrete and steel corresponding to Chinese code as well as create material with specific mechanical properties. Geometric information and section information are combined in line element and shell element components. Two kinds of load types are included in the load component, i.e. point load and uniform line load. Constraint component provides various constraints on the degrees of freedom of nodes, e.g. support and diaphragm. So far, three kinds of analysis are included in Analysis component, i.e. the static analysis, the Newmark analysis and the modal analysis. All the structural information above are assembled together, and sent to the core calculation component. For skyscrapers and long span spatial structures, due to the huge number of degrees of freedom, the conversion between geometries and structural elements may increase running hours. Thus, a parallel conversion strategy is adopted in this series of components. The framework of the series of components and some basic modules are presented in Figure 1.

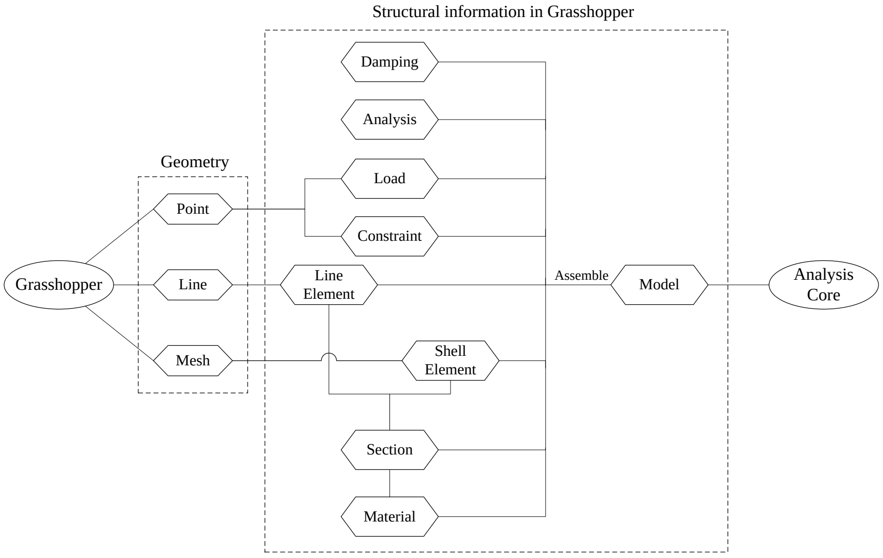

Figure 1. The basic modules of the series of components

5. EXAMPLE

The studied two 14-storey buildings and the modelling logic are illustrated in Figure 2. What should be noticed is that the two models are based on the same parametric modelling logic, which means the change from model 1 to model 2 only requires a few adjustments of sliders. The computational accuracy and efficiency of the analysis core was verified by Fu et al (2015). MCFT and Kent-Park concrete are adopted as material of shell and line elements, respectively. Material properties and geometric information of sections are shown in Table 1. For analytical simplicity, ground motions are applied only in the transverse direction of the structure. In order to make the medium acceleration spectra of the records fit well with the design acceleration spectrum specified in Chinese code (2010), two ground motions are adopted from the ground motions selected by He (2017), i.e. Superstition Hills at Brawley Airport Station, Northridge earthquake at Nordhoff Fire Station and Manjil earthquake at Abbar Station. The peek ground accelerations (PGA) of three waves are amplified to 400gal. Figure 3 illustrates the top displacement time histories.

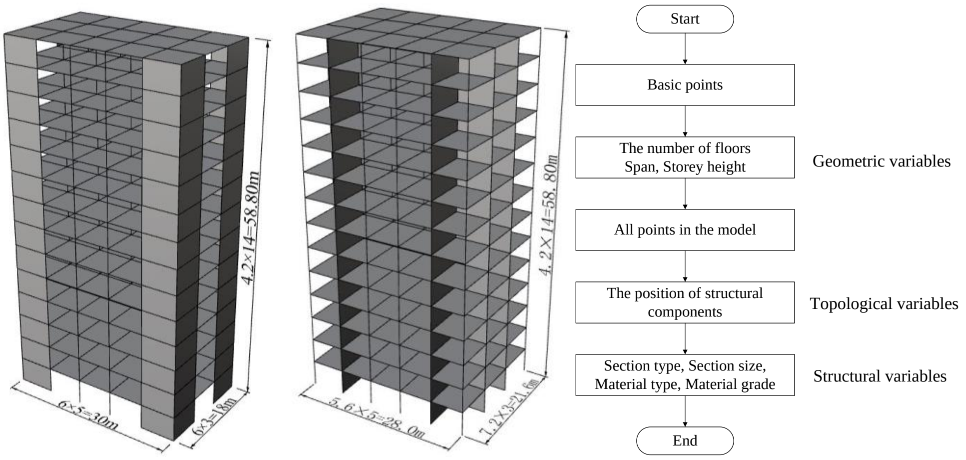

Figure 2. Structural models and modelling logic in Grasshopper

Table 1. Material and geometric information of sections

Parameters	**Beam**	**Column**	**Shear wall**
Section size(m)	0.6×0.3	0.8×0.8	0.2 (thickness)
Concrete maximum strength (N/m^2)	3.25×10^7	3.25×10^7	3.25×10^7
Elastic modulus of concrete (N/m^2)	3.25×10^{10}	3.25×10^{10}	3.25×10^{10}
Steel yield strength (N/m^2)	4.0×10^6	4.0×10^6	4.0×10^6

Note: Floor thickness is 0.15m.

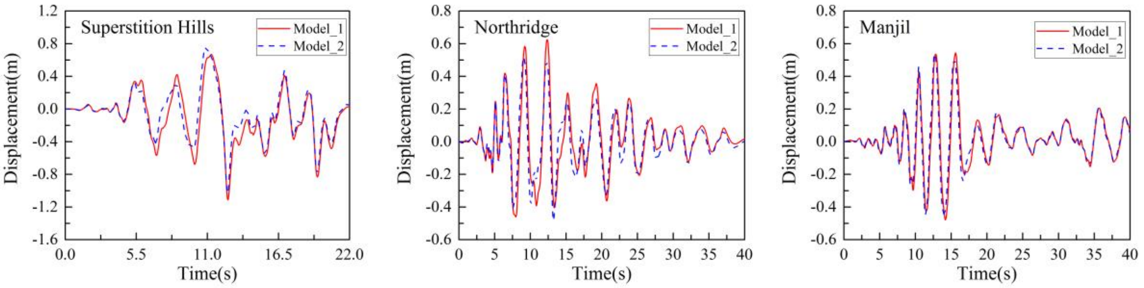

Figure 3. Top displacement time histories of structures

6. CONCLUSION

To consider structural seismic performance in parametric design, a parallel finite element analysis tool is developed as a plugin in Grasshopper. The importance of seismic analysis in multi-objective optimization is emphasized, and the corresponding calculating methods are discussed respectively. Two parallel computing strategies, the parallel state transformation procedures(PSTP) and the parallel factorization of Jacobian(PF), are adopted to accelerate the dynamic analysis. The series of components achieve the data transformation between Grasshopper and the finite element program, which vigorously promotes the speed of structural engineering merging with other architectural fields.

7. ACKNOWLEDGMENTS

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