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A real-time hybrid testing based on restart-loading technology for viscous damper

Guoshan Xu**[1,2,3], Lichang Zheng [1,2,3], Bin Wu*[4,5], Zhuangzhuang Ji [4], Zhen Wang [4,5] and Ge Yang [4,5]

[1] *School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China*
[2] *Key Lab of Structures Dynamic Behavior and Control, Ministry of Education, Harbin Institute of Technology, Harbin 150090, China*
[3] *Key Lab of Intelligent Disaster Mitigation, Ministry of Industry and Information Technology, Harbin 150090, China*
[4] *School of Civil Engineering and Architecture, Wuhan University of Technology, Wuhan 430070, China*
[5] *Hainan Institute of Wuhan University of Technology, Sanya 572000, China*

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Abstract. Real-Time Hybrid Testing (RTHT) requires the numerical substructure calculations to be completed within the defined integration time interval due to its real-time loading demands. For solving the problem, A Real-Time Hybrid Testing based on Restart-Loading Technology (RTHT-RLT) is proposed in this paper. In the proposed method, in case of the numerical substructure calculations cannot be completed within the defined integration time interval, the experimental substructure was returned back to the initial state statically. When the newest loading commands were calculated by the numerical substructure, the experimental substructure was restarted loading from the initial state to the newest loading commands so as to precisely disclosing the dynamic performance of the experimental substructure. Firstly, the methodology of the RTHT-RLT is proposed. Furthermore, the numerical simulations and experimental tests on one frame structure with a viscous damper are conducted for evaluating the feasibility and effectiveness of the proposed RTHT-RLT. It is shown that the proposed RTHT-RLT innovatively renders the nonreal-time refined calculation of the numerical substructure feasible for the RTHT. The numerical and experimental results show that the proposed RTHT-RLT exhibits excellent performance in terms of stability and accuracy. The proposed RTHT-RLT may have broad application prospects for precisely investigating the dynamic behavior of large and complex engineering structures with specific experimental substructure where a restarting procedure does not affect the relevant hysteretic response.

Keywords: accuracy; dynamic performance; real-time hybrid testing; restart loading viscous damper

1. Introduction

1.1 Background and motivation

Traditional seismic testing methods include quasi-static testing (Xu *et al*. 2017, Mourão *et al*. 2022), pseudo-dynamic testing (Mahin and Shing 1985, Devin and Fanning 2019), and shaking table testing (Lu *et al*. 2007, Airouche *et al*. 2014). In 1992, Real-Time Hybrid Testing (RTHT) was proposed by Nakashima *et al*. (1992) based on the pseudo-dynamic testing, in which the specimen was loaded in a real-time mode instead of the quasi-static mode. When conducting RTHTs, the prototype structure is divided into a numerical substructure and an experimental substructure (Nakashima 2001, Wu *et al*. 2009), and the two substructures are coordinated at their boundary to complete the dynamic analysis and performance evaluation of the whole prototype structure. This method is an economical and efficient way of studying the vibration or dynamic performance of structures, especially it is the best choice for investigating the complex dynamic problems of large and complex structures. Therefore, in the past few decades, a series of RTHTs have been carried out throughout the world (Mercan *et al*. 2008, Calabrese *et al*. 2015, Li *et al*. 2021, Gálmez and Fermandois 2022, Tsokanas *et al*. 2022). It should be noted that in order to ensure the online real-time coupling of the two substructures, both the loading on the experimental substructure and the calculation on the numerical substructure should be conducted in the real-time mode.

The key elements for realizing the real-time loading on the experimental substructure include step-by-step integration algorithms (Bursi *et al*. 2011), time-delay compensation (Wang *et al*. 2020, Shao *et al*. 2021), boundary force measurement methods (Schellenberg *et al*. 2017), high-performance loading control method (Verma *et al*. 2019), high-performance loading equipment (Ning *et al*. 2023a, b), *etc*. Time delay is unavoidable during real-time loading on the specimen; therefore, a series of delay compensation methods have been proposed. Horiuchi *et al*. (1999) found that the impact of time delay on the test system can be equivalent to increasing a negative damping. When the negative damping exceeds the damping of the structure itself, the structure as a whole will be in a state of negative damping. Furthermore, for solving the delay

*Co-corresponding author, Ph.D., Professor,
E-mail: wub@whut.edu.cn
**Corresponding author, Ph.D., Associate Professor,
E-mail: xuguoshan@hit.edu.cn

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problem, a time-delay compensation method based on polynomial interpolation (Horiuchi *et al*. 1999) and a time-delay compensation method based on linear acceleration interpolation (Horiuchi and Konno 2001) were proposed. Since then, many researchers have proposed a series of time delay compensation methods (Wallace *et al*. 2005, Ahmadizadeh *et al*. 2008, Chen and Ricle 2009, Ning *et al*. 2023b). In order to improve the loading stability and accuracy, several high-performance loading control methods were proposed. Gao *et al*. (2013) proposed a new servo-hydraulic actuator motion control strategy for RTHT. Wang *et al*. (2018a) proposed the equivalent force control method with a varying sampling number for accomplishing the test with complicated numerical substructure and experimental specimen. Xu *et al*. (2022) proposed a three-variable control method with velocity positive feedback to improve the stability and accuracy of the RTHT.

The methods to realize real-time calculation on the numerical substructure include reducing the model complexity and improving computing power, *e.g*., using high-performance computing equipment. The simplified calculation models were mostly used for simulating the numerical substructures in the traditional RTHTs (Horiuchi *et al*. 1999, Darby *et al*. 2001, Jung *et al*. 2007). However, this method inevitably affects the simulation accuracy and may make it difficult to simulate complicated engineering structures. Therefore, it is essential to investigate a more realistic model for developing RTHT. One possible way is using self-compiled finite element programs to simulate numerical substructures for improving the calculation ability. For example, Chen and Ricles (2012), Saouma *et al*. (2012), Wang *et al*. (2018b) and Lu *et al*. (2020) developed finite element programs based RTHTs, which greatly improved the ability of the RTHT to solve complex engineering problems. However, the degrees of freedom of the numerical substructure are also limited. In order to improve the calculating ability, high-performance computing equipment is also an available measure. Ferry *et al*. (2014) developed Cybermech, a parallel real-time hybrid test platform, under the Linux system which uses 15 cores rather than a single-core processor for improving the computing efficiency. Tang *et al*. (2022) established the RTHT framework based on GPU and Matlab. In case of the integration time interval is 20 ms and single-precision data is used, the maximum degrees of freedom of the numerical substructure can reach up to 27000, whilst the framework based on CPU can only achieve 3888 under the same conditions, which significantly improves the applicability of the RTHT.

These literature review shows that some issues and challenges regarding the real-time conducting of the RTHT are not yet resolved and seriously restrict the development and application of the RTHT for complex structures or dynamic systems.

1.2 Scope

The real-time calculating of the numerical substructure and the real-time loading of the experimental substructure are the key elements of the RTHT for precisely disclosing the dynamic performance of the experimental substructure. Two kinds of strategies had been adopted to guarantee the real-time calculation of the numerical substructure. One is improving the calculation probability of the experimental platform, and another is reducing the complexity of the numerical model. Even though great efforts have been made, these methods are inevitably conducted at the expense of losing model accuracy and/or increasing experimental platform costs. The nonreal-time refined calculating of the numerical substructure, *e.g*., the precise finite element model, is still impossible for the RTHT. For solving this problem, this paper proposes RTHT based on Restart-Loading Technology (RTHT-RLT), which aims to render the nonreal-time refined calculation of the numerical substructure possible for the RTHT.

In this paper, the background, motivation and scope are introduced in Section 1. The RTHT-RLT is proposed in Section 2. The numerical simulations are conducted to evaluate the proposed method in Section 3. The proposed method is validated by experimental tests on one frame structure with a viscous damper in Section 4. The conclusions are summarized in Section 5.

2. Methodology of RTHT-RLT

The RTHT requires the real-time online coupling of the experimental loading and the numerical calculation. Correspondingly, the performance of the RTHT was influenced by two kinds of delays, namely the physical delay and the computational delay. The physical delay denotes the time required for the actuator to receive the command and arrive at the specified position, and the computational delay denotes the time required for the calculation of the numerical substructure at each integration step. A series of delay compensation methods (Wang *et al*. 2020, Horiuchi *et al*. 1999, Chen and Ricles 2009, Ning *et al*. 2023b) were proposed for compensating the physical delay so that the real-time loading on the experimental substructure can be realized for precisely disclosing the dynamic performance of the experimental substructure. The loading targets on the experimental substructure are calculated by the step-by-step integration algorithm, and the corresponding calculation time is denoted by the computational delay. Specifically, the computational delay should be less than the integration time interval in RTHT so that the loading actuator can move smoothly step-by-step and reach the specified position within the specified time; otherwise, the loading actuator must wait for the newest loading target and which may move like a pause-and-go mode so as to the dynamic performance of the experimental substructure cannot be precisely disclosed. The simplification of the numerical substructure model is one possible way to reduce the computational delay, while the accuracy of the numerical models is inevitably reduced. Precise numerical models are certainly the better choice for the RTHT. However, this may lead to the numerical calculation not being completed within the specified time, *i.e*., the integration time interval. Generally speaking, the nonreal-time calculating of the refined numerical substructure model was impossible for the RTHT, which has severely restricted the development and application of the RTHT.

For solving this problem, this paper proposes RTHT-RLT, which aims to render the nonreal-time refined calculation of the numerical substructure possible for the RTHT. In the proposed method, in case of the numerical substructure calculations cannot be completed within the defined integration time interval, the experimental substructure was returned back to the initial state statically. When the newest loading commands were calculated by the numerical substructure, the experimental substructure was restarted loading from the initial state to the newest loading commands so as to precisely disclosing the dynamic performance of the experimental substructure. Fig. 1 shows the schematic diagram of the RTHT-RLT. The RTHT-RLT is composed of three modules, namely the real-time calculation system, the experimental loading system, and the restart loading module. The first two modules are consistent with the traditional RTHT. The restart loading module is the key element of the RTHT-RLT, which serves for restart loading on the experimental substructure, *i.e.*, the data storage, the reset loading command generation, and the restart operation. Specifically, at the end of each integration step, the restart loading module stores the newest loading target and merges the displacement from the initial state to the newest loading target. Then generate reset loading commands, *e.g.*, quadratic function, to the experimental loading system for driving the experimental substructure to the initial state statically. The experimental substructure waits at the initial state until the newest loading target is received and stored. Hereafter all loading targets are sent to the experimental loading system for loading the specimen to precisely disclose the dynamic performance of the experimental substructure. The transducers of the actuator measure the reaction force and displacement response of the specimen. The restart loading module receives these measured responses and compares these responses with the previous step responses to determine whether the repetition accuracy is satisfied or not. If so, the reaction force is sent back to the real-time calculation system and the step-by-step integration algorithm forwards to the next step; otherwise, repeat loading until the accuracy is satisfied. The procedures of the proposed RTHT-RLT are summarized as follows.

(1) Initializing the parameters of the numerical substructure, the step-by-step integration algorithm, and the initial conditions of the investigated structure, *etc*.

(2) The newest loading target is calculated by the step-by-step integration algorithm based on the calculated reaction force of the numerical substructure and the measured reaction force of the experimental substructure, and the newest loading target is sent to the restart loading module.

(3) The restart loading module stores the newest loading target and merges the displacement from the initial state to the newest loading target for generating the overall loading targets. Furthermore, it generates the reset loading commands for driving the experimental substructure to the initial state statically, and the waiting commands at the initial state until the newest loading target is received and stored. Sends all loading commands, namely the overall loading targets, the reset loading commands, and the waiting commands, to the experimental loading system.

(4) The experimental loading system generates loading signal to the controller and loads the experimental substructure according to received loading commands, namely the overall loading targets, the reset loading commands, and the waiting commands. Measures and feeds back the measured reaction force and displacement response to the restart loading module.

(5) The restart loading module compares the measured responses with the previous step responses to determine whether the repetition accuracy is satisfied or not. If so, the

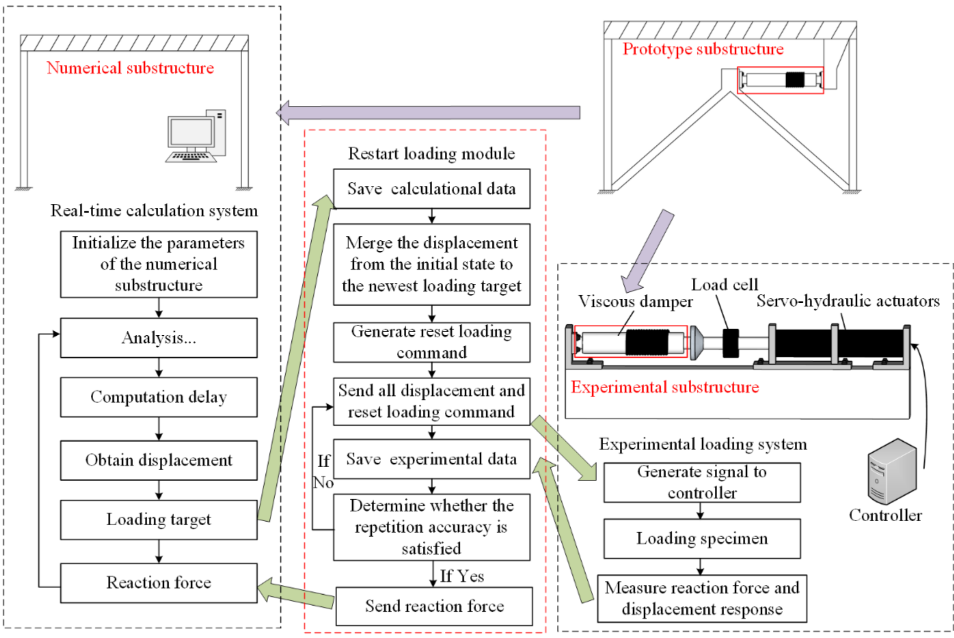


Fig. 1 Schematic diagram of RTHT-RLT method

reaction force is sent to the real-time calculation system and the step-by-step integration algorithm forwards to the next step to the next step; otherwise, repeat loading until the accuracy is satisfied.

(6) Repeat steps (2)-(5) until the end of the test.

The key element of the RTHT-RLT is the restart loading module, which renders the computational delay bigger than the integration time interval possible for the RTHT. On the other hand, the repetition accuracy is easily satisfied benefiting from versatile delay compensation methods. This method breaks through the limitations of real-time calculation in traditional RTHT and inevitably has broad application prospects in the RTHT of large and complex structures. However, it should be noted that the success of the proposed method depends on the repeatability of the performance of the experimental substructures. Specifically, the same experimental results should be obtained from a series of restart loading on the specimen. The method may not be available for the specimens with properties in terms of fatigue sensitivity or plastic deformation.

3. Numerical simulations

3.1 Numerical model

One single-story frame structure with a viscous damper, as shown in Fig. 2, is selected as an example to demonstrate the feasibility and effectiveness of the proposed RTHT-RLT. When conducting RTHT on this kind of structure, the viscous damper is chosen as the experimental substructure loaded by the experimental loading system, and the frame is the numerical substructure simulated in a computer. This paper aims to propose the RTHT-RLT and verify the feasibility of the method. Therefore, one linear mass-stiffness-damping model is assumed for the investigated structure in this paper. The equation of motion at the *i*-th integration step can be expressed as

$$M_N a_{N,i} + C_N v_{N,i} + K_N d_{N,i} = -M_N a_{g,i} - R_{\mathrm{E},i} \quad (1)$$

where M_{N}, C_{N}, and K_{N} are the mass, damping, and stiffness matrices of the numerical structure, respectively; a_{N}, v_{N}, and d_{N} are the acceleration, velocity, and displacement vector of

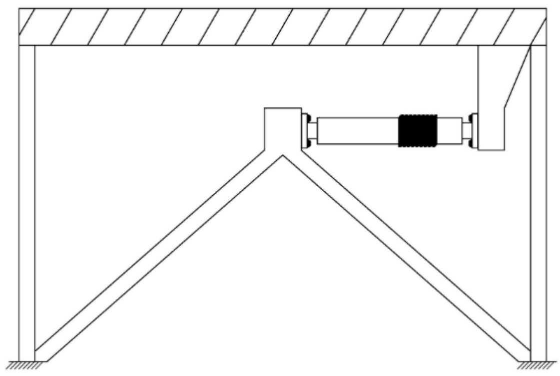


Fig. 2 Schematic diagram of frame structure with a viscous damper

the numerical structure, respectively; $R_{\mathrm{E},i}$ is the restoring force of the viscous damper; a_{g} is the acceleration wave of ground motion; subscript i means the integration time step. The mass, damping, and stiffness parameters of the frame part are M_{N} = 1.62 × 106 kg, C_{N} = 2.879 × 105 N·s/m, and K_{N} = 3.2 × 107 N/m, respectively. The nonlinear mechanical model of the damper is simulated by

$$R_{\mathrm{E},i} = 4000 * sgn(v_i)|v_i|^{0.5} \quad (2)$$

In the simulation, the servo-hydraulic actuator is simulated by second-order transfer functions, as shown in Eq. (3).

$$G_{\mathrm{Actuator}}(s) = \frac{100 \times 100}{s^2 + 2 \times 0.8 \times 100s + 100 \times 100} \quad (3)$$

The ground motion adopts El Centro (NS, 1940) with a peak ground acceleration of 30 gal and a duration of 37 s. The central difference method is employed in this paper for solving Eq. (1), and the integration time interval is set up to be 0.01 s. The real-time calculation system needs to solve the numerical model 3700 times. Since the linear model is adopted in this paper, the calculation time is negligible.

3.2 Simulation schematic

The computational delay is usually dependent on the nonlinearity and the DOFs of the numerical model, the computational ability of the computer, as well as data transmission, *etc*., which may even vary during the process of one test. For convenience, one constant delay, namely 0.023 s, is assumed to simulate the overall computational delay in this paper. That means the restart loading on the experimental substructure should be conducted at each integration time step since the computational delay is bigger than the integration time interval.

The flow chart of the numerical simulation program of RTHT-RLT is shown in Fig. 3, where subscript T and Δt mean the duration of seismic excitation and the integration time interval, respectively. Compared with the numerical simulation program of conventional RTHT, the program of RTHT-RLT is a double loop system, namely the external loop and the internal loop.

The external loop comprises by seismic excitation module, numerical integration module, loading displacement storage module, reset displacement calculation and storage module, and force selection module. The seismic excitation module is used to read the external excitations, *i.e*., acceleration earthquake wave of ground motion. The numerical integration module is used to conduct numerical simulation by the step-by-step integration algorithm, *i.e*., the central difference method. The loading displacement storage module is used to save the loading displacement targets in vector **A**. The reset displacement calculation and storage module is used to generate the reset displacement loading commands $D_{\mathrm{E},i}$ according to the current position, *e.g*., quadratic function from the current position to the initial position, generate the waiting commands, and stored the loading targets, the reset displacement loading commands, and the waiting

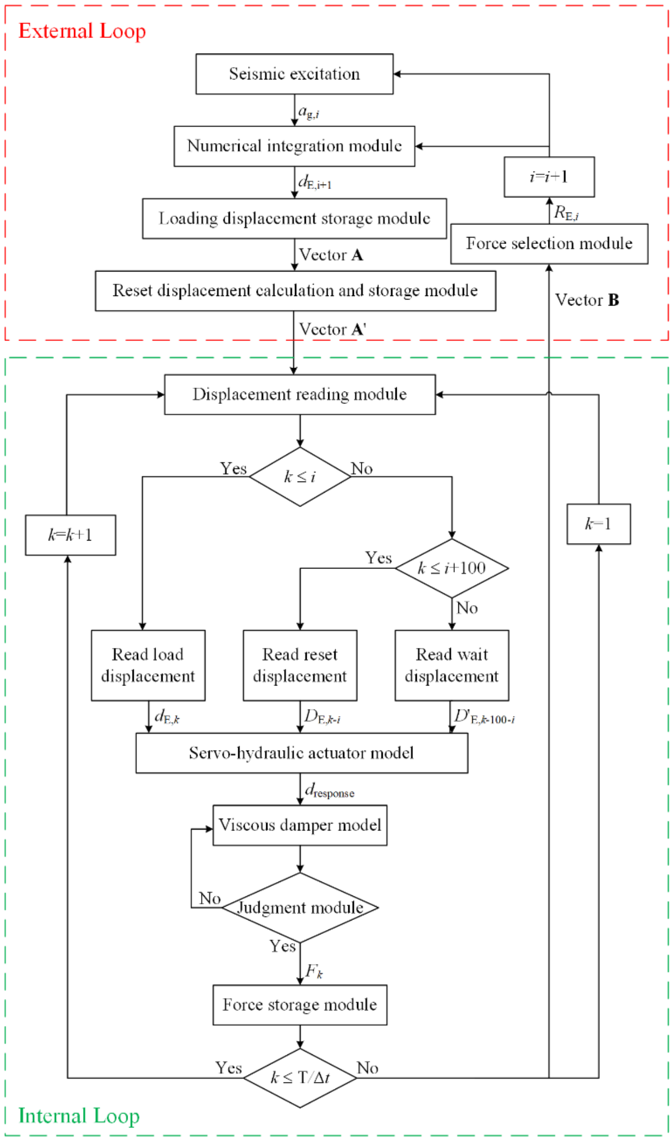


Fig. 3 Flow chart of the numerical simulation program of RTHT-RLT

displacement loading commands, and the waiting commands in vector **A**'. Finally, sends vector **A**' to the internal loop. The function of the force selection module is to select the reaction force at the current moment in vector **B** and transfer it to the numerical integration module.

The internal loop comprises a displacement reading module, servo-hydraulic actuator model, judgment module, viscous damper model, and force storage module. The displacement reading module reads and transfers the stored displacement in vector **A**' successively. The servo-hydraulic actuator model is used to complete the loading on the specimen and measure corresponding reaction forces. One second-order transfer function was used to simulate the dynamic performance of the servo-hydraulic actuator. The function of the force storage module is to store the reaction forces calculated by the viscous damper model in vector **B**. The Judgment module is to analyze the loading error in order to determine if the dynamic performance of the specimen is repeated. If yes, sends the newest measured reaction force to the external loop; otherwise, sends the restart loading commands vector **A**' to reload until the repetition accuracy is satisfied.

That means the internal loop program should be run in real-time for better simulating the actual tests. However, the external loop is run at a slow rate for simulating the long-time numerical simulation. Therefore, the Rate Transition module is used to separate the operating frequency of internal and external loops in the numerical simulation program. Generally speaking, the program was separated into two parts with different sampling periods, as shown in the red and green parts in Fig. 3, respectively. In the simulation, the sampling period of the green part is set to 0.01 s, the reset process is set up to be 1 s, the sampling period of the red part is set to 38 s.

The numerical simulation scheme is presented according to the methodology of RTHT-RLT, as shown in Fig. 4. The scheme is mainly composed by six modules, namely the numerical substructure, the experimental substructure, the servo-hydraulic actuator model, the central difference method, the displacement restart processing module, and

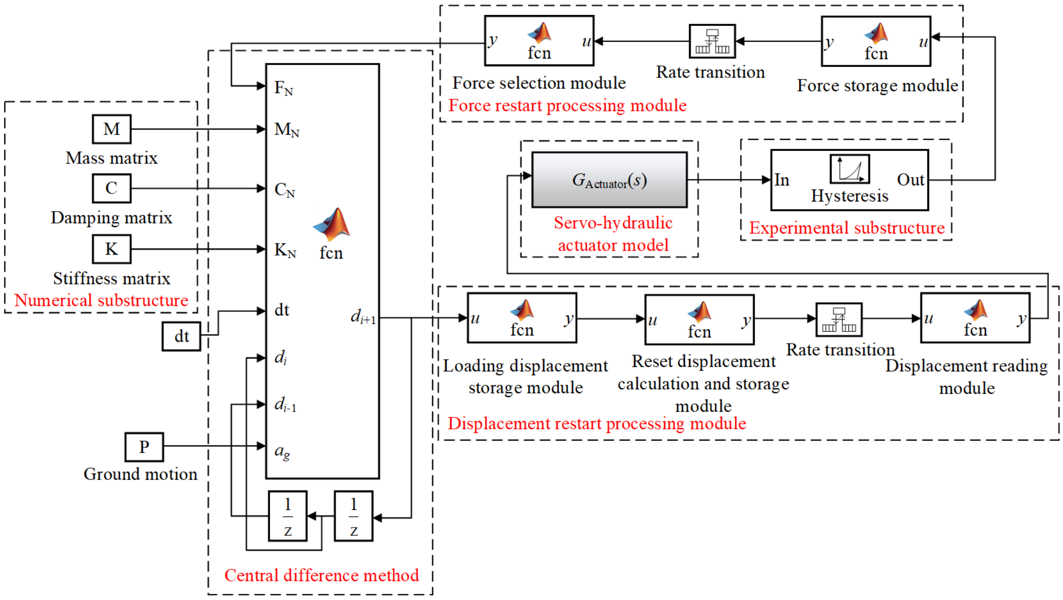


Fig. 4 Schematic diagram of numerical simulation

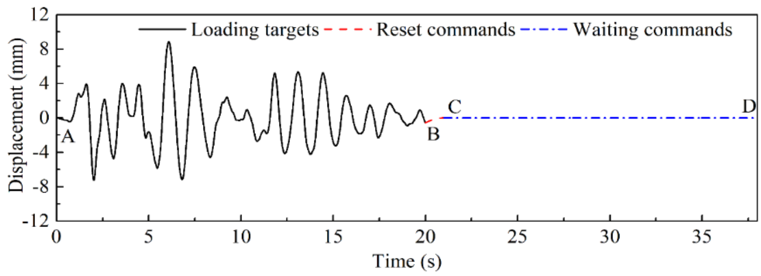


Fig. 5 One period of loading commands

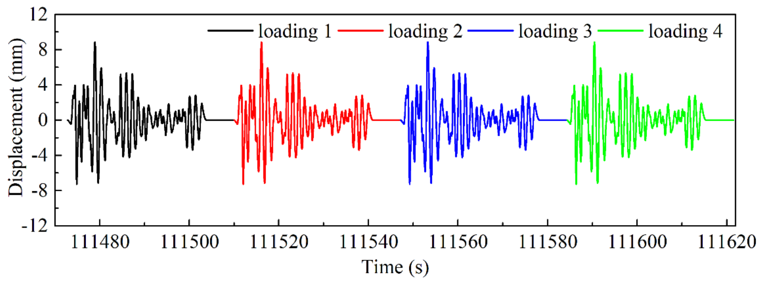


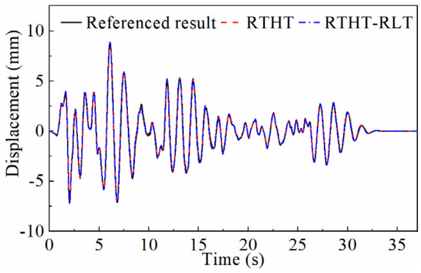
Fig. 6 Partial displacement command of Numerical simulation analysis

the force restart processing module.

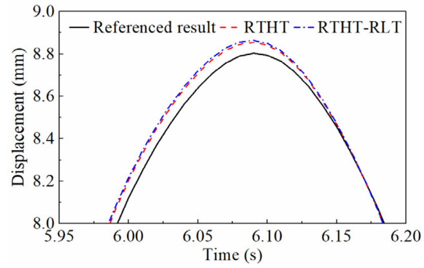
3.3 Simulation results

Fig. 5 shows one period of restart loading commands at 2000th step, in which three-stage loading on the experimental substructure can be obviously found, *i.e.*, the loading targets as shown in stage AB, the reset commands as shown in stage BC, and the waiting commands as shown in stage CD.

Fig. 6 shows parts of the loading displacement commands from the numerical simulation of the RTHT-RLT, in which one can easily observe the periodic process in terms of target reloading, reset, and waiting. For comparison purposes, the traditional RTHT and pure numerical simulation were also conducted. The results of the pure numerical simulation are considered as the referenced results in this paper. The displacement responses of referenced result, RTHT, and RTHT-RLT are shown in Fig. 7. The performance indicators of the results of the RTHT-RLT compared to that of the RTHT and the referenced result, in terms of amplitude deviation, root mean square and correlation coefficient, are summarized in Table 1. As can be seen from Table 1, the amplitude deviation, root mean square, and correlation coefficient of the result of RTHT-RLT compared to the RTHT are 0.11%,



(a) Displacement time history



(b) Closed-up view

Fig. 7 Displacement response of RTHT-RLT

Table 1 Performance indicators of simulation results

Methods	Amplitude deviation	Root mean square	Correlation coefficient
RTHT	0.11%	0.88%	99.99%
Referenced result	0.7%	5.73%	99.85%

0.88%, and 99.99%, which indicates the high accuracy of the RTHT-RLT. Similar conclusion can be drawn from Fig. 7(b). Due to the control errors of the servo-hydraulic actuator, the amplitude deviation, root mean square, and correlation coefficient of the result of the RTHT-RLT compared with the referenced result are 0.7%, 5.73%, and 99.85%. The errors are negligible and the results indicate the feasibility and effectiveness of the RTHT-RLT for the viscous damping specimen.

4. Experimental validations

4.1 Experimental set-up

One single story frame structure with a viscous damper, as shown in Fig. 2, was used as an example to conduct a series of RTHT-RLTs at the Structural and Seismic Testing Center, Harbin Institute of Technology, for validating the feasibility and effectiveness of the proposed method. The block diagram of the RTHT-RLT on the structure is shown in Fig. 8. The mass, stiffness, and damping of the frame structure are 36000 kg, 1.42 kN/mm, and 9050 kN·s/mm.

The RTHTs on this viscous damping structure were also conducted, and the corresponding results were compared with those of the RTHT-RLT for evaluating the accuracy of the proposed method. The ground motion adopts El Centro (NS, 1940) with a peak ground acceleration of 30 gal and a duration of 6 s. The central difference method is employed in this paper for solving Eq. (1), and the integration time interval is set up to be 0.01 s.

The Specific testing cases are listed in Table 2. In case RTHT-RLT-1, each period of restart loading was set to be 7 s such that the test duration was 4200 s. In case RTHT-RLT-2, each period of restart loading was set to be 8 such that the test duration was 4800 s. Of course, the test duration of the traditional RTHT is 6 s.

4.2 Experimental results

Fig. 9 shows two periods of restart loading displacement commands from the RTHT-RLTs. From the result of the RTHT-RLT-2 as shown in Fig. 9(a), three-stage loading on the experimental substructure can be observed for each period. Generally speaking, stages AB and DE are the loading displacement targets, stages BC and EF are the reset displacement commands, and stages CD and FG are the waiting displacement commands. Similar three-stage loading implementation procedure can be observed from the result of the RTHT-RLT-2 as shown in Fig. 9(b), *i.e.*, stages AB and EF are the loading displacement targets, stages BC

Table 2 Testing cases

Cases	Period of restart loading (s)	Test duration (s)
RTHT-RLT-1	7	4200
RTHT-RLT-2	8	4800
RTHT	-	6

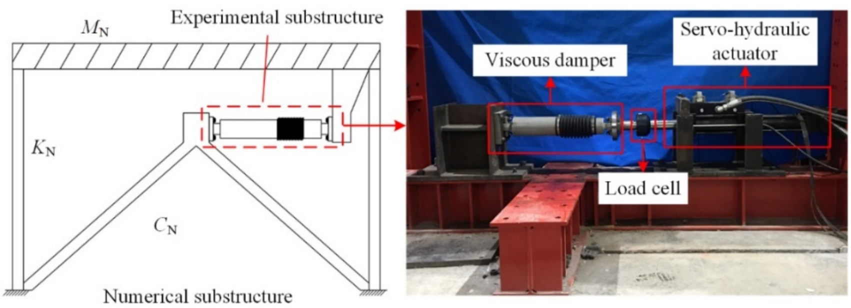
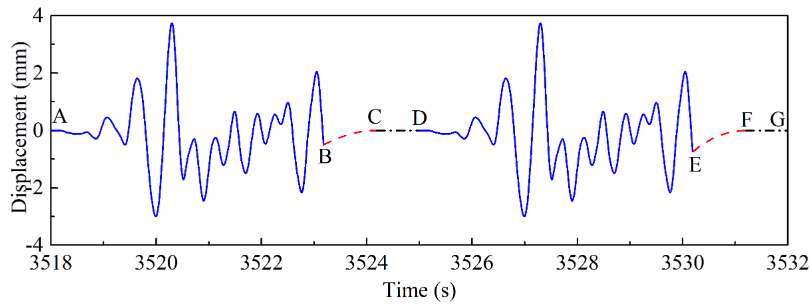
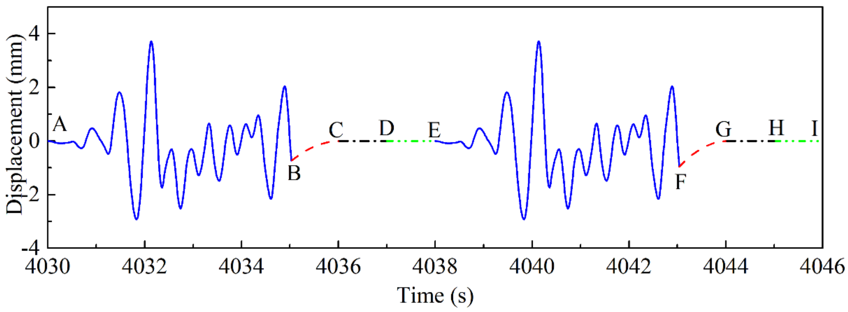


Fig. 8 Block diagram of RTHT-RLT on viscous damping structures

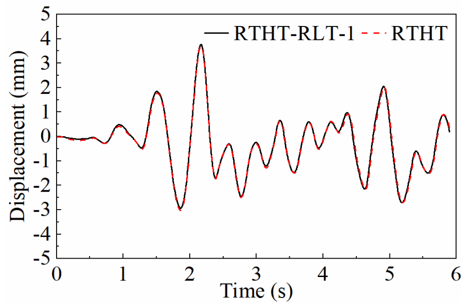


(a) RTHT-RLT-1

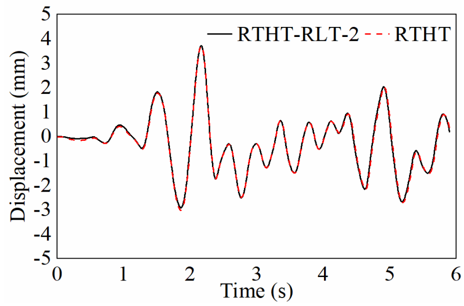


(b) RTHT-RLT-2

Fig. 9 Two periods of restart loading displacement commands of RTHT-RLTs



(a) RTHT-RLT-1 vs RTHT



(b) RTHT-RLT-2 vs RTHT

Fig. 10 Comparison of experimental results

Table 3 Performance indicators of experimental results

Case	Amplitude deviation	Root mean square	Correlation coefficient
RTHT-RLT-1	1.74%	6.83%	99.77%
RTHT-RLT-2	0.20%	6.30%	99.80%

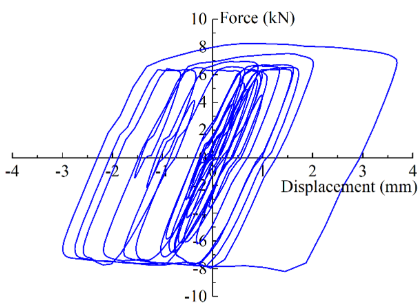


Fig. 11 Hysteretic curve of viscous damper

and FG are the reset displacement commands, stages CDE and GHI are the waiting displacement commands. The difference between Figs. 9(b) and 9(a) is one more second waiting, see stages DE and HI, as well as predetermined in Table 2.

The hysteretic curves of traditional RTHT, RTHT-RLT-1, and RTHT-RLT-2 are shown in Fig. 11. From Fig. 11 one can see that three experimental results agree well with each other, which indicates the effectiveness of the RTHT-RLT for the viscous damper specimen.

5. Conclusions

In this paper, a Real-Time Hybrid Testing based on Restart Loading Technology (RTHT-RLT) was proposed for solving the problem induced by large computational delay. The numerical simulations and experimental validations were carried out to verify the feasibility and effectiveness of the proposed method. The main conclusions are summarized as follows.

(1) Novel RTHT-RLT was proposed. In the proposed method, in case of the numerical substructure calculations cannot be completed within the defined integration time interval, the experimental substructure was returned back to the initial state statically. When the newest loading commands were calculated by the numerical substructure, the experimental substructure was restarted loading from the initial state to the newest loading commands so as to precisely disclosing the dynamic performance of the experimental substructure. The restart loading technique makes the nonreal-time calculation of precise numerical substructure model feasible for the RTHT.

(2) Numerical simulations on one frame structure with a viscous damper were conducted for evaluating the feasibility and effectiveness of the proposed RTHT-RLT. The numerical results show that the proposed RTHT-RLT innovatively renders the nonreal-time refined calculation of the numerical substructure feasible for the RTHT. It is shown from the numerical simulation results the amplitude deviation, root mean square, and correlation coefficient of the result of RTHT-RLT compared to the RTHT are 0.11%, 0.88%, and 99.99%, which indicates the high accuracy of the RTHT-RLT. The amplitude deviation, root mean square, and correlation coefficient of the result of the RTHT-RLT compared to the referenced result are 0.7%, 5.73%, and 99.85%, which indicates the feasibility and effectiveness of the RTHT-RLT for the viscous damping structures.

(3) Experimental tests on one frame structure with a viscous damper were conducted for evaluating the feasibility and effectiveness of the proposed RTHT-RLT. The experimental results show that the proposed RTHT-RLT innovatively renders the nonreal-time refined calculation of the numerical substructure feasible for the RTHT. It is shown from experimental results that the displacement responses of RTHT-RLTs agree well with those of the traditional RTHTs. The amplitude deviation, root mean square, and correlation coefficient of the RTHT-RLT-1 compared to the RTHT are 1.74%, 6.83%, and 99.77%, respectively. The amplitude deviation, root mean square, and correlation coefficient of the RTHT-RLT-2 compared to the RTHT are 0.20%, 6.30%, and 99.80%, respectively. The results indicate the feasibility and effectiveness of the RTHT-RLT.

The proposed RTHT-RLT may have broad application prospects for precisely investigating the dynamic behavior of large and complex engineering structures with specific experimental substructure where a restarting procedure does not affect the relevant hysteretic response. The potential feasibility of the proposed technique includes viscous dampers, magnetorheological dampers, tuned liquid dampers, metal-rubber elastic supports, etc. However, the effectiveness of the proposed method for these devices deserves further investigation.

Data availability

Data are available on request from the authors.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Author contributions

Guoshan Xu designed the methodology, wrote the original draft of the manuscript, and acquired the funding. Lichang Zheng curated the data, wrote the original draft of the manuscript, and validated the results. Bin Wu conceptualized the study and acquired the funding. Zhuangzhuang Ji curated the data, and visualized the study. Zhen Wang discussed the results and revised the manuscript. Ge Yang discussed the results and revised the manuscript.

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