



Experiments on Coupled Technique for Adjacent Similar Buildings

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ABSTRACT

Increasing the population, urbanization has led to rapid construction of buildings. Due to space constraints and an increase in land cost, these buildings are built too close to each other and can cause damage under dynamic actions such as earthquakes. A new technique, known as structural coupling, has been developed recently, has found very effective in dissipating the dispersive vibrations. So far using coupling technique, adjacent dissimilar buildings are connected through a coupling device, such that it can reduce the dynamic response of the structure. The application of the structural coupling technique becomes challenging for similar buildings due to their in-phase behavior under dynamic loads. In the current research, the seismic performance of similar buildings with the coupling technique is experimentally tested on a shake table. A three storey model has been simulated using a unidirectional shake table with the scaled ground motion. Similar building construction uncertainties are accounted for in the study with slight variations in their dynamic properties. The connection devices used are bracings and passive viscoelastic dampers. The results obtained confirm the effectiveness of structural coupling technique with various configurations of dampers for similar buildings over seismic protection individual buildings.

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1. INTRODUCTION

Earthquakes are highly unpredictable in their frequency place and time of occurrence. The main reason for the failure of buildings during an earthquake is due to inadequate design to resist seismic forces. All buildings in seismic zones should be constructed by following the design codes, so that, the damage could be minimized and catastrophic failure can be avoided during the aseismic event. Thence, the behavior of buildings during an earthquake needs to be studied in advance to formulate such design. The seismic performance of a building is defined as the measure of recorded or expected ability of the structure to sustain due functions (safety and serviceability) during and after the earthquake. The damage and other parameters of the building during the earthquake depends on a number of factors. One of the main factors is the response of the building to the ground motion. The response involves the following parameters, deformation, velocity, and acceleration demands of structural components of the building. The parameters

which can be considered for estimation of seismic performance of buildings are residual storey drift ratio, peak floor velocity, floor acceleration, and peak story drift ratio at every floor in the corresponding direction [1]. Usually, a set of buildings that serve the same facilities, such as educational institutes, residential quarters, etc., are often have identical structural designs and are built adjacent to each other, which makes them dynamically similar to each other. Seismic protection provided individually to each building is uneconomical. Rather, structural coupling technique can effectively reduce the seismic response of buildings simultaneously proves to be economical. From the past earthquake case studies [2], it can be clearly seen that the dynamically similar buildings also undergo damage during an earthquake. Hence, it is very important to study the possibility of improving the seismic behavior of dynamically similar buildings economically.

Pounding behavior in buildings which are adjacent to each other during the earthquakes causes serious damage and ultimate fatality. To prevent these, researchers have

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proposed to connect the adjacent structures using a connected control technique known as structural coupling technique. It has found to be very efficient in minimizing seismic response between two adjacent structures. The seismic behaviour of adjacent structures with similar and dissimilar dynamic characteristics, subjected to five different seismic excitations [3]. The study concluded that the effect of pounding from adjacent buildings on the seismic behavior of a structure is more pronounced for the end structures in a row. The effect of collision of adjacent buildings in series is numerically studied for different separation distances. Three alignment configurations under nine ground motions, the obtained responses are compared with the no pounding case [4]. The seismic interaction between adjacent buildings that are a part and non-symmetric in the plan may pound each other because of significant torsional oscillations [5]. In order to overcome the pounding effect on dissimilar buildings, many studies are carried out with connected control techniques. The connected control technique with the rigid links helps to avoid the pounding effect between two dissimilar buildings [6]. A fluid damper connected to the adjacent buildings has been simulated under ground excitation and has concluded that it is the best way for protection of flexible building structures [7]. Another study compared the efficiency of active and passive coupled building control for flexible adjacent dissimilar buildings [8]. But all the above research was limited to dynamically dissimilar buildings. A straight damper connection between dynamically similar buildings is thought to be inefficient as the motion of both the structures will be in the same direction. Few studies have found where behavior has been studied with the combination of coupling technique and other isolation techniques. The behavior of the two similar coupled building was studied with one building base-isolated, and others coupled with viscoelastic dampers. Three cases (both the buildings were fixed at the base, one fixed at the base, and other base-isolated, both the buildings isolated) were studied [9]. It was concluded that the system would be most effective when one building is base-isolated and the other is fixed. Also, this hybrid method was found to be effective in controlling the response under a long duration earthquake as well as a near-fault earthquake. The same hybrid method was adopted to study the seismic performance of podium structures and two similar moment-resisting frames that are isolated at the base [10, 11].

Further, the buildings are connected through passive dampers. This approach enabled the simultaneous optimization of the control performance and the control cost [12]. Few studies were conducted on the modeling of magnetorheological (MR) damper in control studies of adjacent buildings [13, 14]. These studies show the effective use of such damper in this application of coupled technique. All the above research focuses on

making one of the similar buildings dissimilar by providing base isolation or bracing and then connecting those using straight dampers. This hybrid technique is uneconomical as one of the buildings has to be made dissimilar, and then dampers need to be connected. However, coupling techniques can also be adapted to dynamically similar structures with different damper configurations without putting an extra cost on making one of the buildings dissimilar.

The most commonly used passive control damper, which increases the structural damping and dissipating the vibration, is the viscoelastic damper [15]. Most of the research carried out in the past two decades focused on characterizing the VE material properties using a series of harmonic tests at different strain amplitudes, frequencies, and temperatures [16, 17]. A higher-order fractional derivative model can be used to simulate the mechanical behavior of viscoelastic (VE) dampers. This model describes the effects of environmental temperature and excitation frequency with different VE materials [18]. The study on seismic response of a scaled steel structure with added VE dampers shows that VE dampers are very effective in reducing excessive vibration of the test structure due to seismic excitation [19]. Fatigue analyses of buildings with viscoelastic dampers were carried out to reduce the dynamic response of the structure effectively [20, 21]. The analytical and experimental studies were carried out for plan asymmetric structures with viscoelastic dampers [22]. It demonstrated that VE dampers could control the response of asymmetric structures. A steel frame was simulated experimentally with a viscoelastic damper [23]. It was observed that the response of the model reduced as per the design standard. Similarly, another type of viscoelastic damper was used in a structural application to improve seismic performance [24]. Few studies were carried out to verify the coupling technique of adjacent buildings. The seismic performance of VE damper connected coupled buildings was experimentally studied on two adjacent two-degree freedom buildings models [25]. In order to understand the vibration control effect, the earthquake response of connected single-degree-of-freedom (SDOF) building models using hysteresis dampers was studied analytically and experimentally [26]. The study of the coupled buildings was concluded that the dynamic properties and the connector properties influence the behavior of the coupling technique [27]. Also the seismic performance of structure with various connecting devices were studied to reduce the dynamic response [28-33].

The above experimental works are limited to dissimilar building models and SDOF similar buildings models. The numerical and experimental studies have demonstrated the feasibility of these strategies. From the reviews mentioned above, it can be seen that the mechanical and geometrical properties of the buildings and the connectors influence the efficiency of the

coupling technique. In the present study, the potential of the coupling technique has been evaluated for similar adjacent structures when subjected to earthquake motion. Bracings and viscoelastic dampers are used as a connecting element between two adjacent structures. The efficiency of the coupled control method for similar structures entirely depends on the orientation and configuration of connecting elements. Hence, the present study focuses on the effect of connecting elements configuration on seismic control of dynamically similar buildings using the coupled technique.

2. METHODOLOGY

Initially, a numerical analysis has been carried out to finalize the geometrical and mechanical properties of the model. For the fabrication and for validation of the numerical model, the model updating technique was used to correlate the natural frequencies and vibrational modes. This is to ensure that physical behavior is obtained in terms of numerical models. This correlation can be used to obtain the different geometrical and mechanical properties of the model as well as the connector. This analysis was carried out in Sap2000. Then, the uncoupled models were simulated on the shake table subjected to scaled ground motion, and the acceleration data were obtained with accelerometers. Subsequently, the models were coupled using a brace and viscoelastic damper between first and second floors in the structure and subjected to scaled earthquake excitation. Finally, these results were analyzed to verify the effectiveness of the coupling technique to reduce the seismic response of similar structures.

3. STRUCTURAL MODELING

A scaled model of a multi-storied frame structure is fabricated as steel frames and mounted on the shake table. Accelerometers are placed at different levels to record the dynamic response under earthquake loading. Through experimental testing, the natural frequency of the fabricated test models is obtained. Also, the test structure is modeled through the numerical tool, and the numerical model is being updated to match the experimental results.

3.1. 3D Frames Models Two framed buildings models of each three-story are fabricated using steel sections and combined with brace/damper, as shown in Figure 1. Each model has plan dimensions of $0.8\text{m} \times 0.6\text{m}$. The height of each floor is 0.6m and has three floors. The beams and columns are chosen from mild steel tubular square section with $20\text{mm} \times 20\text{mm} \times 1.8\text{mm}$. Each floor is fabricated with a steel plate of 6mm thick welded to the floor beams. As per the above model

dimensions, the mass and stiffness properties of the experimental model is considered for dynamic analysis. Both building models are fixed on a solid shake table mount, and hence the assumption of no soil-structure interaction is valid. Though the same geometric and material properties for both the buildings are considered at the design stage, their dynamic properties may slightly vary due to practical uncertainty in the construction stage. The allowance for such slight variations is accounted for in scaled building models during fabrication by procuring materials from different sources.

3.2. Shake Table and Data Acquisition System

In order to simulate the base movement for the small-scale building models, the unidirectional shake table is used. The shake table with actuator specifications are given in Table 1.

A compact data acquisition (DAQ) system, NI 9234 module with a four-channel dynamic signal acquisition, is used for recording high-precision acceleration measurements. The specifications of the DAQ system are given in Table 2. This DAQ module is compatible with a single-module USB carrier and has compact hardware, ideal for field measurements.

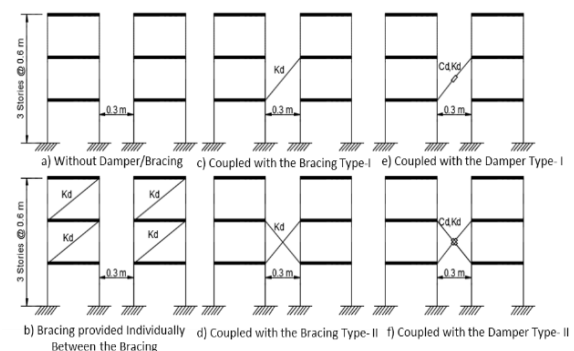


Figure 1. Different configuration coupled system

TABLE 1. Specification of the shake table system

| Uni-Axial Shake Table: Size 2 m x 3 m | |
|---------------------------------------|-------------|
| Payload | 12 Ton |
| Table maximum displacement | ± 75 mm |
| Maximum Velocity | 1 m/s |
| Maximum Acceleration | 3g |
| Frequency | 0 to 100 Hz |
| Actuator | |
| Make | MTS, USA |
| Capacity | 250 kN |
| Stroke | ± 75 mm |

TABLE 2. Data acquisition system

| Product Name | NI 9234 |
|------------------------------|---|
| Signal Ranges | ± 5 V |
| Channels | 4 |
| Sample Rate | 51.2 kS/s/ch |
| Input Configurations | IEPE with AC Coupling, AC Coupling, DC Coupling |
| Noise at Maximum Sample Rate | 50 μ Vrms |
| Connectivity | BNC |

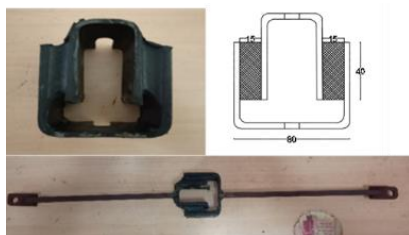
LabVIEW software² interface is used for processing the recorded signals. High sensitivity accelerometers for seismic applications are used for recording the acceleration response of building models, and their specifications are given in Table 3.

3. 3. Passive Control Device-Brace and Viscoelastic Damper

As a connecting element, a brace and viscoelastic dampers are used as passive control devices. The bracing element is chosen from mild steel solid square section with 10mm \times 10mm and length as per between connecting joints. The locally available viscoelastic dampers (Figure 2) are used as a connecting element. The dimensions of the viscoelastic damper are also shown in Figure 2 with length as per between connecting joints. The viscoelastic material is made up of natural rubber with hardness 45-55 as per the vendor's specification³. These connecting elements are installed within individual structures, between two structures, and their performance under seismic excitation is studied. In numerical modelling, the mass of these link elements is ignored.

TABLE 3. Specification of Uni-Axial accelerometer

| Model | PCB-393B04 |
|-----------------|---------------|
| Measuring range | 5 g |
| Sensitivity | 1,000 mV / g, |
| Frequency range | 0.06 - 450 Hz |
| Frequency | Up to 100 Hz |

**Figure 2.** Viscoelastic dampers

4. RESULTS AND DISCUSSIONS

4. 1. Dynamic Properties of 3D Frame Models

The fabricated building models are fixed on the shake table, tested using impact hammer, and the response at the top floor is measured using accelerometers. The time history response signal is post-processed in the frequency domain to obtain the dynamic properties of building models. The obtained first three natural frequencies and corresponding damping ratios are given in Table 4. The tests were repeated to rule out the possible errors during acquisition, and at most care was taken to make sure that the errors related to boundary conditions (fixity of the base) are negligible. Then, the numerical model of the building frame is updated [34] using the model updating technique to match the experimental frequencies. The initial material properties and the updated material properties of the steel used for the fabrication of building models are shown in Table 5. After updating the numerical model, the natural frequencies were compared with that of the experimental building model, as summarized in Table 4. The slight variation in natural frequencies of left and right building models were observed due to fabrication uncertainties. After the update of the model the dynamic behaviour of the numerical model is expected to replicate the real building model. The measured damping ratios of the both building frames were close to each other and very less indicating the need for external damping or bracing to control the vibration.

4. 2. Dynamic Properties of 3D Frame Models

The shake table testing of building frames subjected to scaled EL-Centro (1940) ground motion is carried out. At first, the building frames without any connecting devices (Figure 4a) are tested for their seismic responses. Then each building with bracings provided individually between the floors (Figure 3b) is tested. Further, both the buildings coupled with bracings connection Type-I (Figure 3c) and bracings connection Type-II (Figure 3d) were examined. Finally, both buildings coupled with viscoelastic damper connection Type - I (Figure 3e) and viscoelastic damper connection Type-II (Figure 3f) were tested.

TABLE 4. Dynamic property of building models

| Modes | Experimental frequency (Hz) | | Sap2000 frequency (Hz) | Damping Ratio |
|-------|-----------------------------|-------------|------------------------|---------------|
| | Left model | Right model | | |
| 1 | 5.86 | 5.5 | 5.645 | 0.007 |
| 2 | 17.93 | 16.813 | 17.372 | 0.005 |
| 3 | 31.26 | 28.188 | 28.358 | 0.004 |

² <https://www.ni.com/en-in/innovations.html>

³ <http://www.rsarora.com>

TABLE 5. Material properties of numerical model in SAP

| Model | Young's modulus (Gpa) | Density (kg/m ³) |
|----------|-----------------------|------------------------------|
| Original | 200 | 7850 |
| Updated | 193 | 7820 |

In all the above cases, the acceleration records at the top floor of both building models are recorded. Acceleration response data gives an indication of the effectiveness of each coupling technique in reducing seismic responses. The comparisons of the seismic response in terms of acceleration time history for all the building model cases with and without connecting links are shown in Figure 4. The seismic response of left and right building frames without any connecting devices are different due to slight variation in their dynamic properties. This behaviour was expected as the uncertainties are considered during their fabrication. The maximum acceleration response of each building cases (shown in Figure 3) has been tabulated in Table 6 along with percentage reduction with connecting links. In case of buildings provided with individual bracings, the maximum percentage of reduction in seismic response is observed compared to other cases. This is because the bracing links used in both building frames are eight in total number, whereas, in other cases only two number of link elements in total are used to for their coupling. Hence, providing bracing for individual building may be effective but becomes uneconomical. Therefore, further investigations and comparisons are done by coupling building models with two link elements. Among all the coupled building models, the maximum seismic response reduction is observed for buildings coupled with viscoelastic damper connection type-II. In this case left building response is reduced by 47% while the right building response is reduced by 25%. The considerable variation among the response of left and right building mainly attributes to unsymmetrical damper connection along with slight variation in their dynamic properties. The coupling technique is able to effectively reduce the accelerations of the two structures in the order of 20-50%

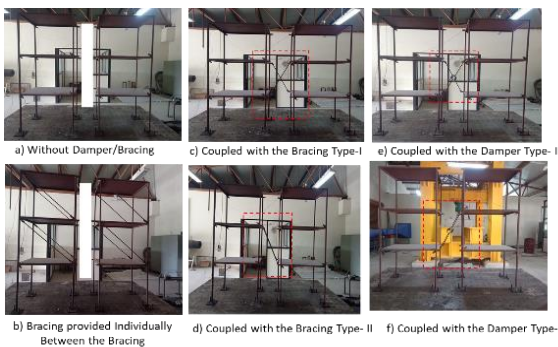


Figure 3. Relative displacement and Drift ratio plots for El-Centro ground motion

TABLE 6. The maximum acceleration response in each

| ConnectionType as shown in Figure 4 | Maximum Acceleration (g) | | Percentage reduction (%) | |
|-------------------------------------|--------------------------|----------------|--------------------------|----------------|
| | Left building | Right building | Light building | Right building |
| Figure 4a | 0.155 | 0.199 | - | - |
| Figure 4b | 0.06 | 0.09 | 61.29 | 54.77 |
| Figure 4c | 0.114 | 0.145 | 26.45 | 27.14 |
| Figure 4d | 0.091 | 0.155 | 41.29 | 22.11 |
| Figure 4e | 0.099 | 0.162 | 36.13 | 18.59 |
| Figure 4f | 0.082 | 0.149 | 47.10 | 25.13 |

with only two link elements. Further, by increasing the number of coupling link elements, the percentage reduction can be increased.

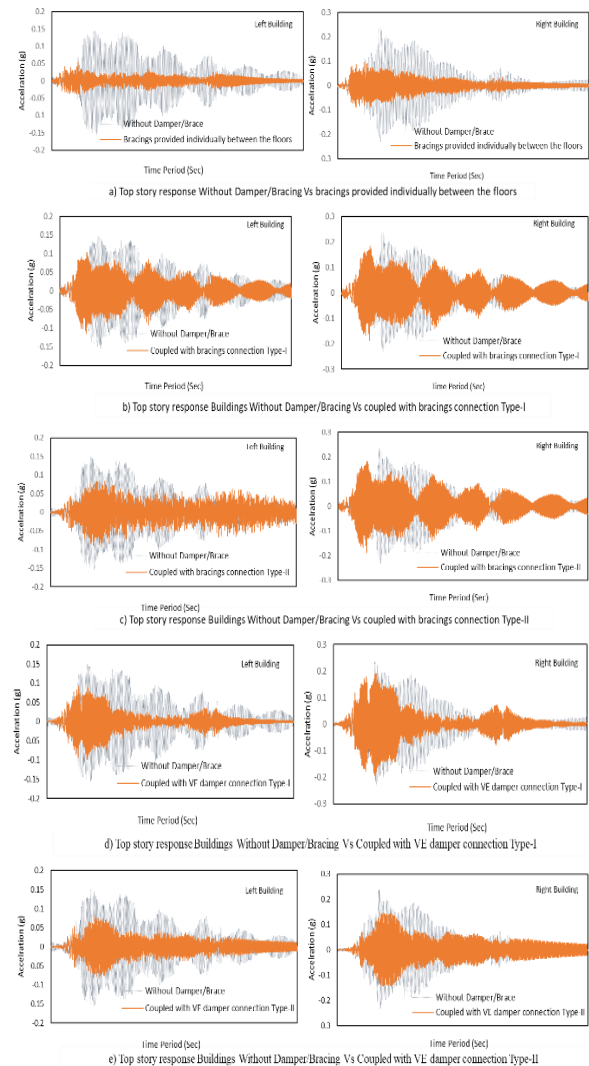


Figure 4. Acceleration record for different configuration of coupled system

5. CONCLUSION

The experiments have demonstrated the possibility of using structural coupling to control the seismic responses of both adjacent similar buildings. The effect of constructional uncertainties on dynamic properties of buildings and its consequence on coupled buildings is studied. The efficiency of the structural coupling technique is evaluated by testing the building frames on shake table excited with scaled seismic ground motions. Studies on the effects of different configurations of link elements in reducing the seismic response of similar buildings has led to interesting results. Providing bracing for both buildings individually can be effective but leads to uneconomical solution. A comparative study with different damper configurations shows that, the alternative diagonal viscoelastic damper configurations are more effective in seismic response reduction.

By increasing the number of coupling link elements, the percentage reduction can be increased. This structural coupling technique can be extended to high-rise buildings with numerical and experimental studies. Further, study can be carried out using the updated numerical model to find the optimal location of the connecting links between the similar buildings without repeated experimental studies.

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Persian Abstract

چکیده

با افزایش جمعیت، شهرنشینی به ساخت سریع ساختمانها انجامیده است. به دلیل محدودیت های فضا و افزایش هزینه زمین، این ساختمان ها خیلی نزدیک به یکدیگر ساخته شده اند و در اثر اقدامات پویا مانند زلزله می توانند باعث خسارت شوند. اخیراً روش جدیدی به نام اتصال اتصال ساختاری ایجاد شده است و در از بین بردن لرزشهای پراکنده بسیار مؤثر است. تاکنون با استفاده از تکنیک کوپلینگ، ساختمانهای مجاور مجزا از طریق دستگاه اتصال به یکدیگر متصل می شوند، به گونه ای که می تواند پاسخ پویای سازه را کاهش دهد. استفاده از روش اتصال ساختاری به دلیل رفتار درون فاز آنها تحت بارهای پویا برای ساختمانهای مشابه چالش برانگیز می شود. در تحقیق حاضر، عملکرد لرزه ای ساختمانهای مشابه با تکنیک کوپلینگ به صورت آزمایشی بر روی میز لرزش آزمایش شده است. مدل سه طبقه ای با استفاده از جدول لرزش یک طرفه با حرکت زمین مقیاس شبیه سازی شده است. عدم قطعیت ساخت و سازه های مشابه در ساختمان با تغییرات جزئی در خصوصیات دینامیکی آنها در نظر گرفته شده است. دستگاه های اتصال مورد استفاده بریس ها و میراگرهای ویسکوالاستیک منفعل هستند. نتایج به دست آمده تأثیر تکنیک اتصال جابجایی ساختاری را با تنظیمات مختلفی از میراگرها برای ساختمانهای مشابه بر روی ساختمانهای انفرادی لرزه ای تأیید می کند.
