Measuring Centers of Special Targets in Digital Still Images and Movie Frames: Approach and Evaluation

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Abstract: Digital cameras are undergoing explosive developments. As a result, high-resolution digital cameras have become very affordable, especially with the latest growth in smart phone technologies. Hence, the usage of existing measuring technologies and the development of new measuring technologies utilizing digital cameras is in high demand. This paper utilizes special black and white patterns, the so-called targets, to measure the relative displacement between two points. The paper introduces a new approach in measuring the location of their centers that is based on best fitting the transition zones to straight lines. The intersection of these lines produces the location of the center with sub-pixel accuracy. A special experimental rig was designed and built to evaluate the approach and compare the measurements to those obtained by a conventional position transducer connected to a data acquisition system. In the first part of the paper, the accuracy of the position transducer and the experimental setup is discussed. It is shown that the accuracy of the setup is much greater than the measurement expected from the digital images. Based on this, it was used as a reference system to evaluate the approach. In the second half of the paper, the approach is evaluated based on monitoring two targets. One of them is fixed and serves as a reference point, whereas another one is floating. The latter can move along the linear bearing system axis, which is orthogonal to the axis of the camera lens. The displacements of the floating target in respect to the fixed target were measured by a position transducer connected to a data acquisition system. The relative displacement of the floating target is captured by the digital camera and is based on the current location of the floating and fixed targets. This paper shows adequate accuracy of the approach and provides recommendations on the ways of keeping it at high accuracy for practical applications in experimental earthquake engineering.

1 INTRODUCTION

Digital still imaging cameras are commonly used as an affordable tool for measuring surface deformations and displacements of test specimens in experimental studies. Digital still images can also be extracted from digital movies as individual frames. This provides an opportunity to use digital cameras in quasi-static and dynamic experiments as well. Certainly, in the latter case the main limitation is going to be the number of frames per second. With the current development in digital cameras, access to high-resolution cameras with rates greater than the normal 30 frames per second is rapidly increasing. In addition, the cost of cameras is dramatically decreasing because of high demand by several industries: autonomous cars, surveillance monitoring cameras, and smart phones, to name a few. Therefore, the usage of digital still images or movie frames is steadily increasing in many fields, including experimental earthquake engineering. A digital imaging camera has become an affordable and easy to access tool for monitoring surface deformations and relative displacements (Ogorzalek et al 2017, as an example). In addition, it represents one of the most cost-effective ways of measuring the relative displacements of a complex system with several moving parts. An example is presented in Figure 1. This image shows a typical suspended ceiling system consisting of a grid and lay-in panels. Because of the gap between the grid and the panels, the movements of the grid are different from those of the panels. To monitor all these displacement

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differences, an installation of many position transducers is needed, which is not practical. In addition, conventional instrumentation is not preferred because it can alter the system performance due to the added weight of instrumentation. This can be addressed by utilizing measurement techniques based on the digital images. In this case, the movements of the panels and the grid can be monitored by these non-contact measurements.

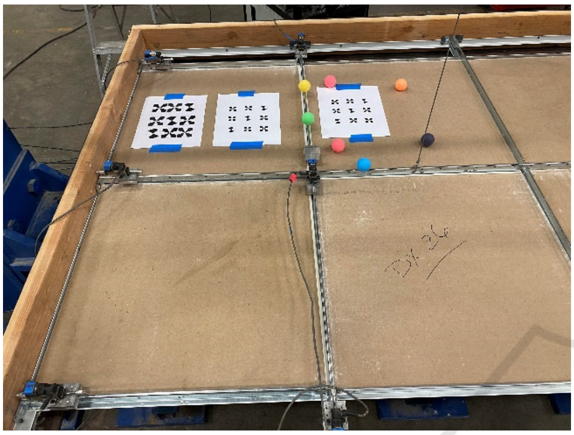

Figure 1: Monitoring grid and panel displacements in testing of suspended ceiling system.

2 MOTIVATION

The main motivation was to develop a reliable technique of non-contact displacement measurements when installation of many position transducers is not practical or too expensive. In addition, accuracy estimation is crucial for achieving high quality of test data and such, needs to be provided for the analysis of the experimental data. Recommendations on the position of the camera in respect to the experimental setup required to achieve higher accuracy are very valuable too. In addition, the proper selection of settings in digital cameras is also very important to achieve high-quality measurements.

3 EXPERIMENTAL SETUP AND REFERENCE INSTRUMENT

A special experimental setup was developed and assembled to evaluate the accuracy of the monitoring conducted by the targets. As shown in Figure 2, the targets were installed on two vertical boards located in the same plane. Each target represents a special black and white pattern printed on a sheet of paper and attached to the surface to be monitored. Quite a few patterns are used in practical applications with a recent extensive review of their specifics summarized in (Janßen et al 2019).

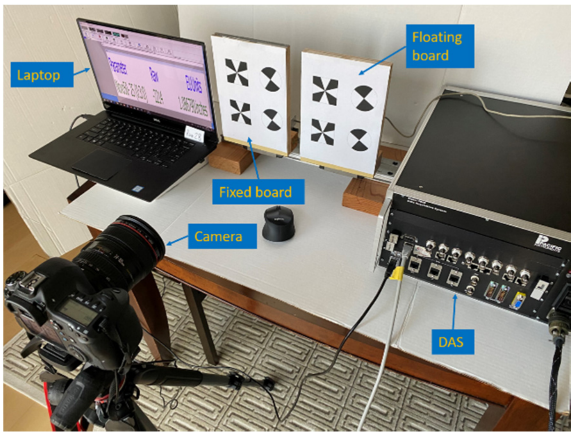

Figure 2: Front view of experimental setup.

Each board shown in Figure 2 was attached to a different carriage of a linear bearing system as shown in Figure 3. One of them was fixed and the other was free to slide along the rail of the linear bearing system. The latter was called a floating carriage. The axis of the linear bearing system was orthogonal to the axis of the camera's lens. As a result, due to the presence of the linear bearing system, both boards were restrained to move in the same plane orthogonal to the camera's lens.

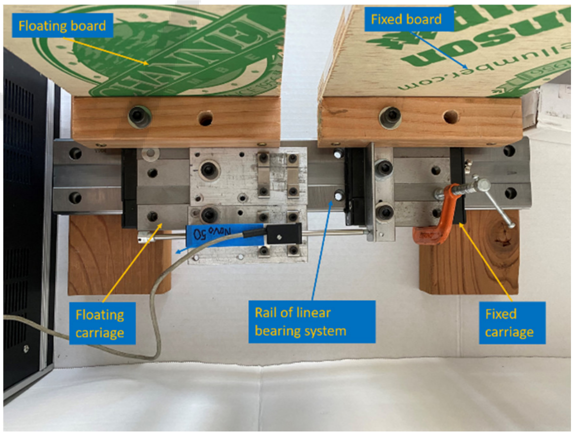

Figure 3: Top view of experimental setup: linear bearing system with carriages.

The relative displacement between the fixed and floating carriages was monitored by a position transducer as shown in Figure 4. This position transducer was used as a reference. The setup utilized TR0050 (Novotechnik U.S., Inc., 2014), a position transducer with a specified linearity of 0.15% of full

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scale. The transducer had a full stroke of 50 mm or about 2 inches. The readings of the position transducer were acquired by PI-6008U, a data acquisition system (DAS) from Pacific Instruments, Inc. (Pacific Instruments, Inc, 2017).

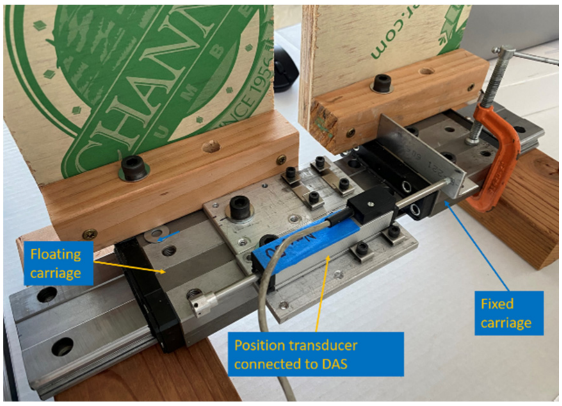

Figure 4: Reference position transducer to monitor relative displacement.

A few targets were installed on the boards as presented in Figure 5. One of them is a black and white target commonly used for laser scanning (see Takhirov, 2010, as an example). The second one, is a target similar to the so-called BOTA8 proposed by (Janßen et al 2019). The target used in this study utilized an opposite colouring pattern when compared to BOTA8. For the purposes of this paper, the discussion of the approach and its evaluation are discussed only for the round target. A full-frame digital camera, Canon EOS 6D DSLR in this particular case, was installed on a tripod to capture the movements of the floating targets.

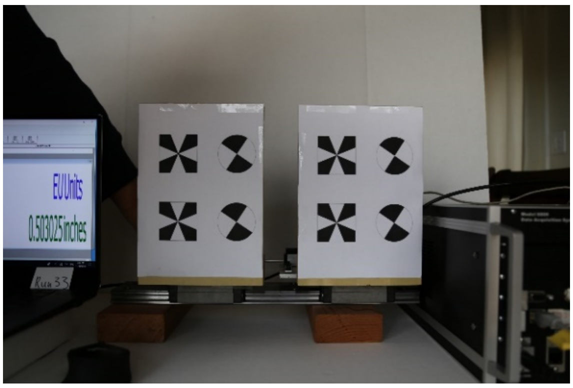

Figure 5: Typical image frame.

A typical still image of the targets is presented in Figure 5. It shows the floating and fixed boards on the right and left sides, respectively. In addition, to achieve real-time correlation to the reference displacement, the latter was displayed on the left side of the screen as shown in Figure 5. Presence of the reference displacement in the same image with the targets is especially important for movie frames because then no time correlation is needed.

4 EVALUATION OF REFERENCE ACCURACY

Prior to evaluating the target monitoring accuracy approach, accuracy of the reference position transducer was measured. It was performed in the following way. High-precision steel calibration blocks were used (Mitutoyo, 2016). The blocks were Grade 0 which ensures that their tolerance is about a few micro-inches (or about 0.0001 mm). The position transducer was calibrated at two points and its readings were checked with several gage blocks at many other displacement points as presented in Figure 6. This plot shows the readings collected by DAS when the position transducer is displaced by various gage blocks. The collected data was averaged over 400 points to obtain a reading of the reference position transducer with a certain gage block. Those points are shown as red circles in Figure 6.

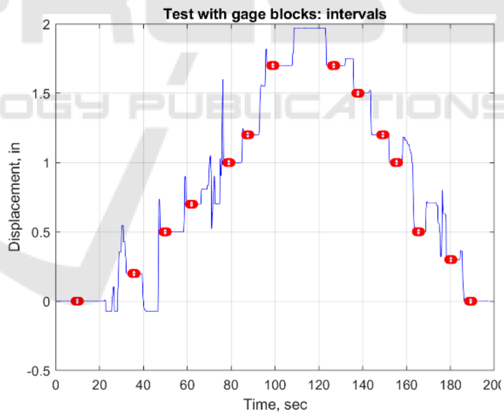

Figure 6: Displacement of position transducer with various high-precision gage blocks.

Each averaged reading was compared to the corresponding gage block and the error between the two values was calculated. It is presented in Figure 7. As it is shown in this plot, the error does not exceed 0.015 mm. Based on the specifications of the position transducer, the expected linearity is 0.15% of full-scale, which equals to 0.075 mm for the 50 mm instrument used herein. Hence, based on this accuracy measurement, it was concluded that the accuracy of this particular transducer is much better than the

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specifications established for their mass production. It is worth noting that the accuracy measurement included possible uncertainties associated with the data acquisition system and DAS accessories (a cable, for example).

These preparatory steps show that this experimental setup has an adequate accuracy for the evaluation of the accuracy of monitoring by targets introduced in this paper.

Figure 7: Error of position transducer with respect to gage blocks.

5 RESULTS OF IMAGE REDUCTIONS: CLOSE PROXIMITY

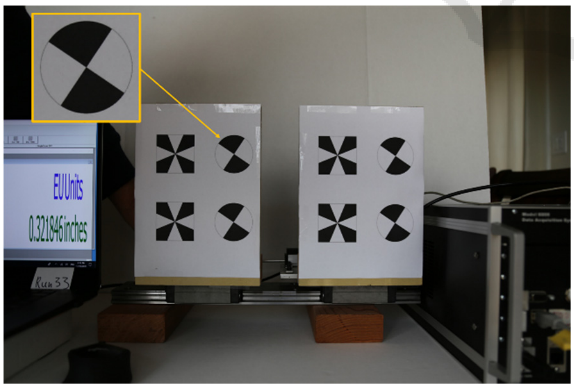

Figure 8: Step 1: find target's pattern in image.

All image manipulations were conducted in the Matlab environment (MathWorks, 2016). The image reduction was based on utilization of the target's specific pattern. It was conducted in two steps. In the first step, the location of the target's pattern shown in Figure 8 was identified based on Fast Normalized Cross-Correlation, FNCC, (Lewis, 1995a and 1995b). In this step, the location of the target's center is estimated with pixel accuracy.

In the second step, the transition points between the black and white zones are determined. Based on the target pattern, points for two subsets are separated from each other. One subset corresponds to a slope of less than 90 degrees whereas another one corresponds to a slope greater than 90 degrees. These subsets are best fit to straight lines as presented in Figure 9.

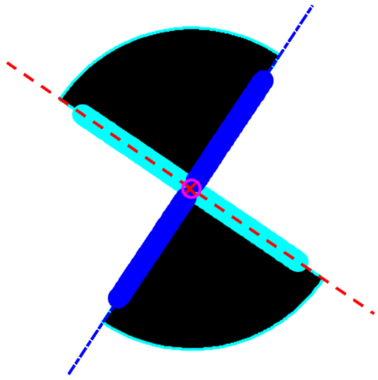

Figure 9: Step 2: Target's center as intersection of two straight lines best fit to the transition points.

As it was noted earlier, step 1 serves as an intermediate step to identify an approximate location of the target's center. This step helps to speed up the calculation of a more accurate estimation of the target's center. The difference between the results of the two steps is presented in Figure 10.

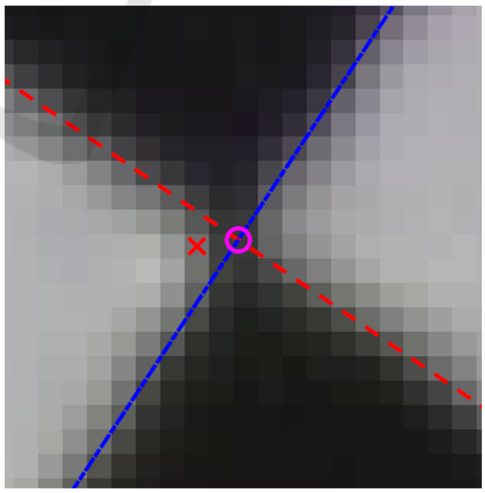

Figure 10: Target's center: step 1 (red cross) and step 2 (magenta circle).

As it can be seen from Figure 10, step 2 estimates the target's center with a subpixel accuracy. Now, if the correlation between the pixels and the engineering

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units is defined, this approach estimates the location of the center in mm with a much higher accuracy than the one based on the FNCC procedure.

The correlation between the pixels and engineering units, mm in this case, was based on measurements of the target's radius in both pixels and mm. A comparison between the measurements of the position transducer and the moving target monitored by the still images, is presented in Figure 11. The plot shows close correlation between the two measurements. It is worth noting that this discussion and this plot is based on the estimation of the relative displacements between the fixed and floating targets.

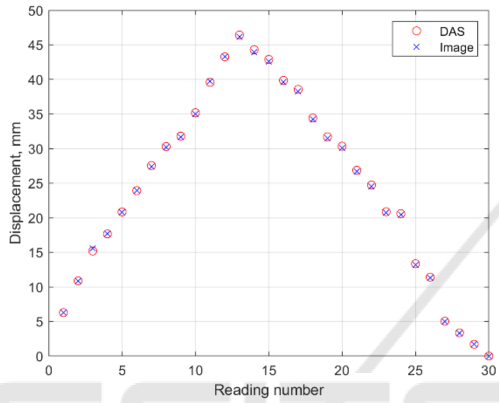

Figure 11: Displacements of target compared to that of the reference position transducer.

An error or the difference between the two measurements does not exceed 0.4 mm as presented in Figure 12. This error is shifted towards negative values when the image measurement is less than the displacement measured by the position transducer. Hence, in this particular case, the displacement measured from the image is underestimated.

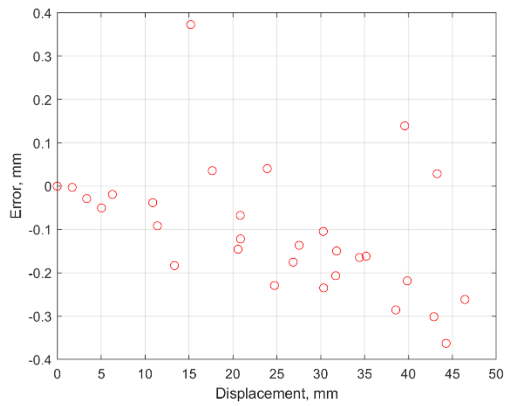

Figure 12: Error of target's center estimation with respect to the reference position transducer.

It is worth noting that the size of each target was about 0.7% of the 3648 pixels by 5472 pixels images taken by this camera. A lens with variable focal distance was used and for this test the focal distance of the images was 32 mm.

The error of 0.4 mm is well below the accuracy of the experimental setup discussed earlier. The accuracy can be increased by correcting the images for the lens distortion and other means. Some of the possible ways of improving the accuracy are discussed below.

6 RESULTS OF IMAGE REDUCTIONS: CAMERA PLACED FURTHER AWAY

To evaluate the approach, a number of tests were conducted with the camera placed further away from the targets. In the first case described above, the camera was placed about 1 meter away from the targets. As a result, the target occupies a relatively large portion of the overall image. By placing the camera further away, the targets occupy a much smaller portion of the image. For the second case considered here, the camera was placed about 5 meters away as presented in Figure 13.

A typical image taken by the camera at this distance is presented in Figure 14. The focal distance of the lens was set at 65 mm. As a result, each target occupies about 0.06% of the 3648 pixels by 5472 pixels image's area.

Figure 13: Camera placed at further way distance.

A smaller relative target size is very important in experimental studies because then the larger surface

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of a test specimen can be included in the same frame for simultaneous visual monitoring.

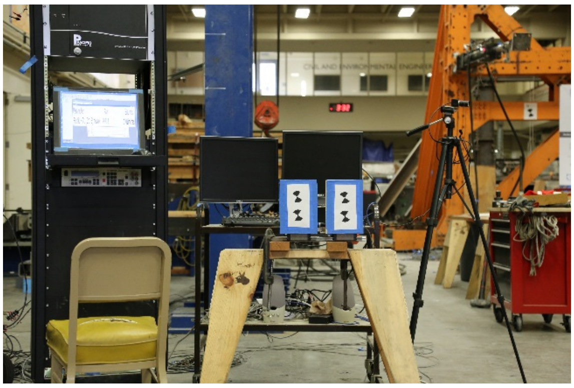

Figure 14: Targets occupy very small portion of the image.

To avoid any possibility of relative movement of the camera, the camera was placed on the strong floor of the test laboratory and all triggering was done remotely. The latter ensures that small but unexpected movements of the camera resulting from pushing the triggering button on top of the camera are completely avoided.

The same experimental setup was utilized as the in the previous case of the closely placed camera. The direct correlation between the actual displacement of the target and image was achieved by combining the displacement output of the DAS into the same image with targets as presented in Figure 15.

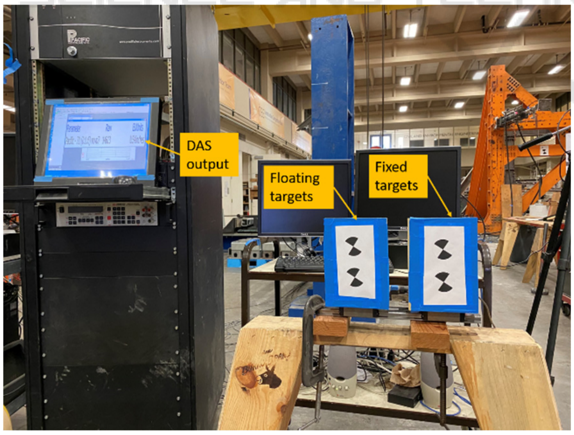

Figure 15: The reference displacement is combined into each image.

A correlation between the pixels and engineering units, mm in this case, were based on measurements of the distance between the top and bottom targets in both pixels and mm. A comparison between the displacement measured by the reference position transducer and the displacement measured from the image is presented in Figure 16.

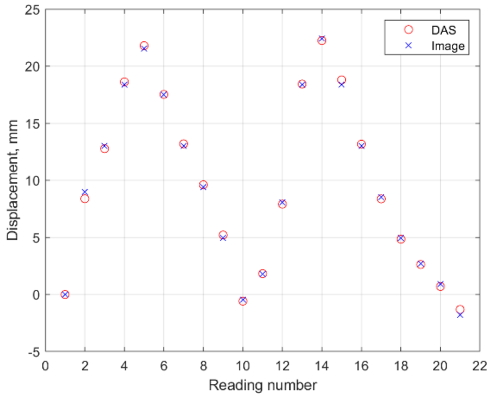

Figure 16: Comparison of the displacement measured from images to that of the reference position transducer.

The error between the two measurements is presented in Figure 17. As presented in the plot, the error between the displacements measured from the images and from the position transducer does not exceed ±0.5 mm. It is worth reminding that this accuracy was achieved from a distance of about 5m, which is quite remarkable. The result is consistent with the one obtained earlier when the camera was placed much closer to the targets.

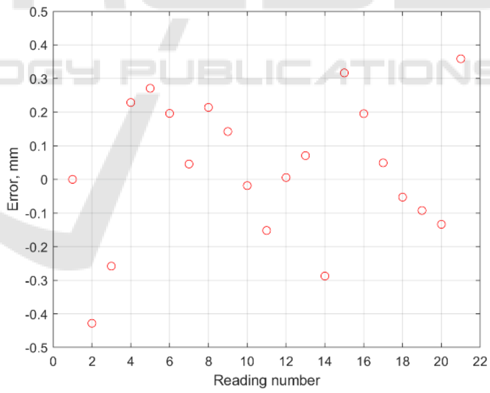

Figure 17: Error between the displacements measured from images and that of the reference position transducer.

This accuracy was achieved based on the following measures. First, the relative size of the target was reduced to about 0.07% of the overall image area. This reduces the effects of the lens distortion. Second, the camera was triggered remotely, so any contact with the camera was excluded to avoid any undesired movements of the camera by pushing on the triggering button. Third, the focal distance of the lens was increased to reduce the effect of the lens distortion. Fourth, a calibration

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factor converting pixels into engineering units was based on a relatively larger distance, a distance between the top and bottom targets. In this case, a small error in the distance measurements will not result in a large error in conversion of pixels into mm. For future applications of the approach in experimental studies, these measures are recommended to be used so adequate accuracy of the measurements can be achieved.

Some other variables affecting the measurements will be studied in future investigations.

7 CONCLUSIONS

This paper utilizes special black and white patterns, the so-called targets, to measure the relative displacement between two points. The paper introduces a new approach in measuring the location of their centers that is based on best fitting the transition zones to straight lines. An intersection of these lines produces the location of the center with sub-pixel accuracy. A special experimental rig was designed and built to evaluate the approach and compare the measurements to those obtained by a conventional position transducer connected to a data acquisition system. In the first part of the paper, the accuracy of the position transducer and the experimental setup is estimated. It is shown that the accuracy of the setup is much greater than the measurement expected from the digital images. Based on this, it was used as a reference system to evaluate the approach. In the second half of the paper, the approach is evaluated based on monitoring two targets. One of them is fixed and serves as a reference point whereas another one is floating. The latter can move along the linear bearing system axis which is orthogonal to the axis of the camera lens. The displacements of the floating target in respect to the fixed target were measured by a position transducer connected to a data acquisition system. The relative displacement of the floating target is captured by the digital camera and is based on the current location of the floating and fixed targets. The paper shows adequate accuracy of the approach and provides recommendations on the ways of keeping it at a high accuracy for practical applications in experimental earthquake engineering.

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