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DAMAGE DETECTION BY MODAL TESTING

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ABSTRACT

The paper describes the application of vibration measurement techniques to detect and characterize significant damage to structures during earthquakes. Modal testing, using ambient and impact vibration methods, was applied to a four-storey steel plate shear wall specimen. The half-scale model of a steel frame infilled with unstiffened thin steel plate shear panels, which was tested until failure under cyclic lateral loading, was subjected to vibration measurements before and after loading. The comparison of vibration measurements before and after the cyclic tests revealed a significant shift in the fundamental frequencies and mode shapes of the frame in the longitudinal and transverse direction for the undamaged and damaged stages. Substantial changes in the fundamental frequencies and mode shapes of the frame could be attributed to a partial column fracture and tearing and crumpling of the shear panels.

KEYWORDS

Ambient vibration; impact test; steel plate shear wall; damage detection; dynamic characteristics; modal analysis

INTRODUCTION

The detection of damage to structures in an earthquake might seem a trivial task, considering the abundance of shattering images after such an occurrence. Often, serious structural damage may be virtually invisible, however, as became evident with many steel framed buildings after the Northridge and Hyogoken-Nanbu earthquakes in 1994 and 1995 respectively. A large number of moment resisting frames sustained severe damage in the beam to column moment connection regions, which only became evident after expensive inspection procedures that required the removal of wall cladding and fire proofing.

The method of modal testing has been used in many cases in an attempt to detect and characterize damage that a structure has endured as a result of earthquakes, wave forces or corrosion. It is a growing field of research since invisible defects in structures such as offshore rigs or buildings where structural members are covered with cladding, can pose severe risks of collapse if not identified and repaired in time. Inspection methods can be very expensive and great benefit can be gained by narrowing the potential damage area with analytical and measuring tools. Considerable effort has been undertaken in the past few years to investigate the relationship between the damage location, the damage type and severity with the corresponding modal parameters. Although the technique of damage detection appears very promising, in practice it still remains very difficult to characterize damage in complex structures in all but the most severe cases.

Since the late 1960's, steel plate shear wall systems have been incorporated in several buildings around the world (Troy and Richard, 1979). The system is essentially a vertical plate girder where the columns represent the girder flanges and the beams act as transverse stiffeners. In most cases, design of the plates was based on the assumption that the plates do not buckle before attainment of the shear yield strength. This resulted in relatively thick plates or, alternatively, excessive use of stiffeners in both the vertical and horizontal directions, which often negated the beneficial cost savings. Recent research has shown that thin unstiffened web plates, combined with the surrounding frame, can be an efficient lateral load resisting system by mobilizing tension field action in the thin plate. The latter system was used for the study presented here.

The testing of a half scale model steel frame with steel plate infill shear panels at the Centre for Frontier Engineering Research in Edmonton, Alberta, (Driver *et al.*, 1995) presented an opportunity to use modal testing on the undamaged and damaged structure to establish a pattern of frequency and mode shape shifts particular to this type of structure and damage. The tests were conducted in collaboration with researchers at the University of Alberta as part of a collaborative project on the seismic performance of steel plate shear walls. Results of the vibration study are presented here together with a discussion of the findings.

DESCRIPTION OF EXPERIMENTAL TESTS

Vibration measurements were conducted on the specimen before and after cyclic testing. In both cases the specimen was not attached to the loading and support mechanisms to allow for free vibration measurements without artificial external constraints. The first phase of testing led to the information regarding the dynamic characteristics of the steel plate shear wall specimen alone, with no damage due to the application of external loading. After the shear wall specimen was loaded to failure in a gradually increasing load cycle sequence, the second phase of vibration tests was carried out in a similar manner. The aim was to capture the effects of plate buckling and tearing, weld cracking or tearing and member fracture on the dynamic characteristics of the shear wall frame specimen. The intent was to investigate whether any damage in the infill plates or the frame, such as buckling, tearing or cracking, would be reflected as a shift of modal frequencies in the frequency response function (FRF) of the system. Since the specimen was not loaded with realistic storey masses and natural frequencies would thus be disproportionally high, the modal test results should be considered for comparative purposes only and should not be interpreted as absolute values.

The test specimen was a 50% scale model representing one bay of the lower four storeys of an office building. The first storey was 1.93 m high with the upper top three storeys each 1.83 m. The columns, which consisted of W310×118 wide flange sections of grade 300W steel, were kept constant throughout the frame. Medium depth wide flange beams, W310×60, were used for the bottom three storeys while a deep stiff beam, W530×82, was used above the top storey to anchor the tension field forces generated in the shear plate. The thicknesses of the shear wall infill panels were 4.54 mm, 4.65 mm, 3.35 mm and 3.40 mm in panels 1 to 4 from the bottom storey to the top storey, respectively. All the beam to column connections were fully welded to create fixed moment connections. The shear panels were continuously welded to the surrounding beams and columns by means of a fish plate connection detail. Figure 1 shows the frame specimen in the loading apparatus.

A load distribution beam was attached to the top of the columns, to apply a constant gravity load of 720 kN to each column throughout the test . Equal horizontal loads were applied at each storey level by means of hydraulicactuators, cycling between predetermined displacements of increasing amplitude. More details on the test setup, the cyclic loading sequences and the load-deflection curves (Fig. 2) are available in Driver's report (1995).

The bottom shear plate sustained the most severe damage from buckling and yielding (Fig. 3). Repeated folding caused several small tears in the plate, which resulted in a gradual degradation of load carrying capacity and

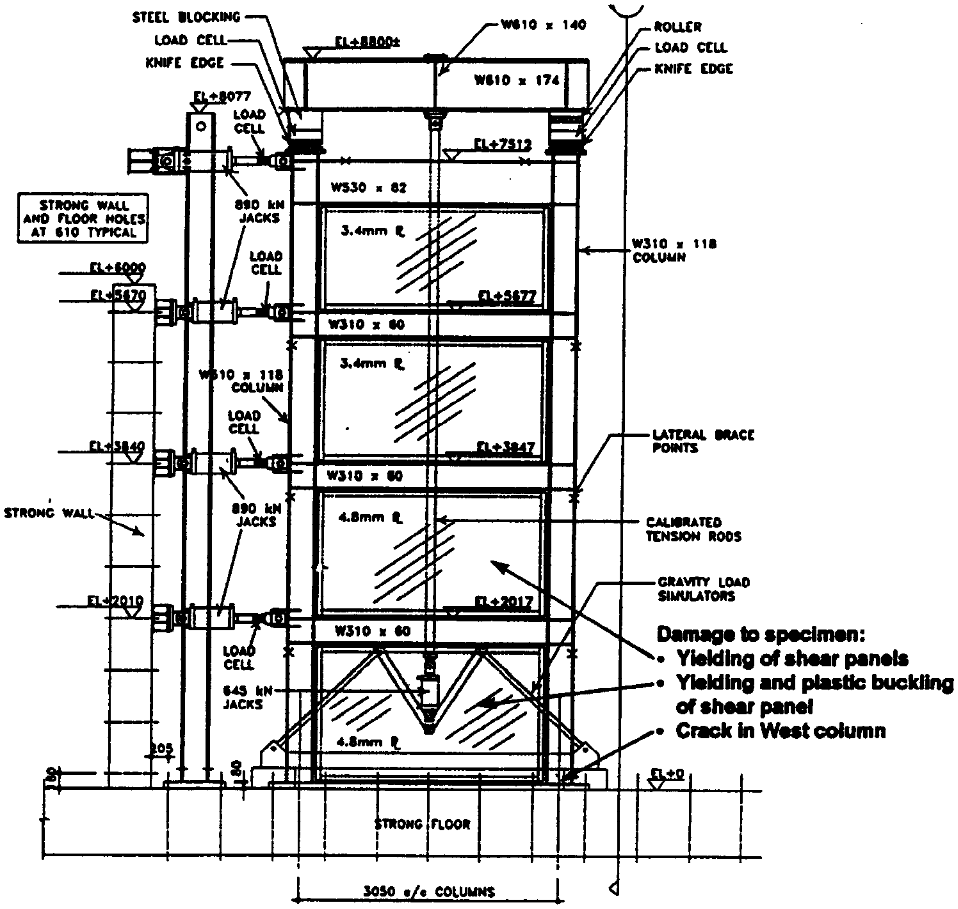

Figure 1: Steel plate shear wall test specimen (Driver *et al.*, 1995)

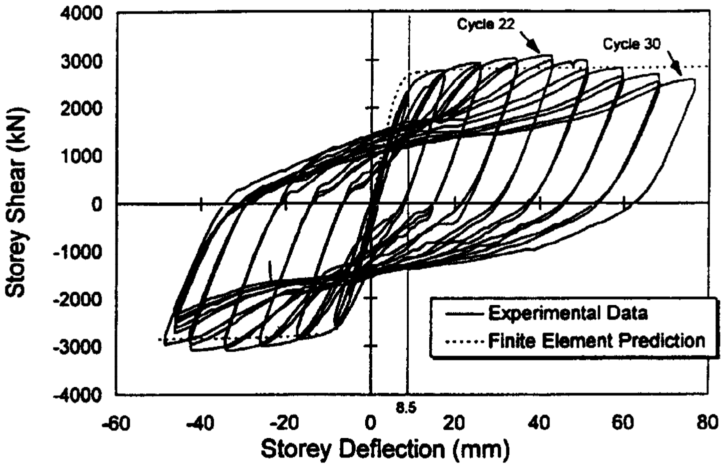

Figure 2: Load-displacement curve of test frame (bottom storey) (Driver *et al.*, 1995)

stiffness with increasing load cycles. Tears also developed in the corners where the shear panels were attached to the beams and columns (Fig. 4). All the tears propagated very slowly as loads were redistributed to adjacent arts of the frame. A crack developed in the west column starting from the weld to the base plate (Fig. 5) during the 30th load cycle, resulting in a sudden load drop and termination of the test. Before this occurrence, the remaining load capacity of the frame was about 85% of the maximum load and the stiffness was about 88% of the initial elastic stiffness (Fig. 2).

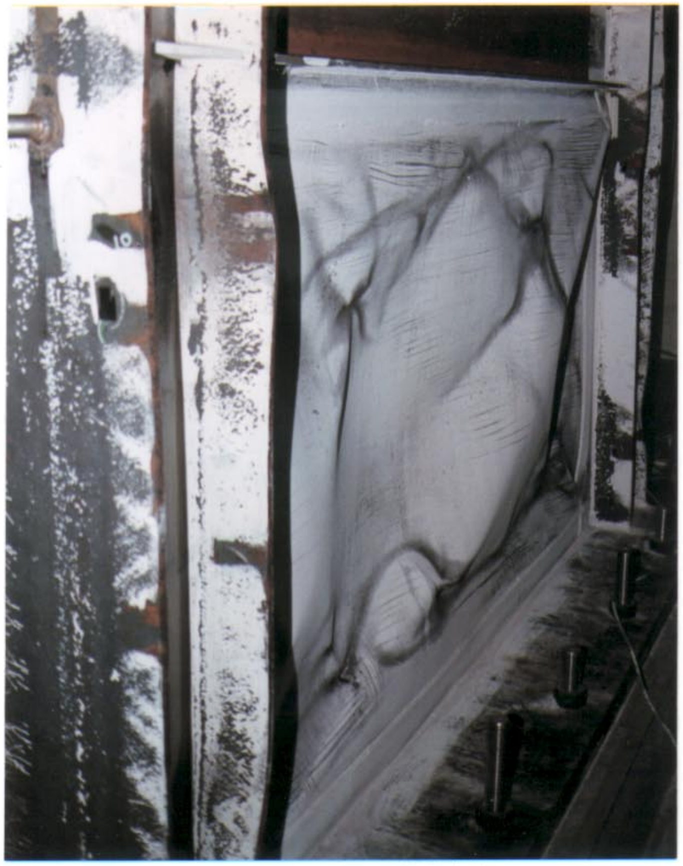

Figure 3: Bottom storey of frame showing deformed steel plate and buckled column members

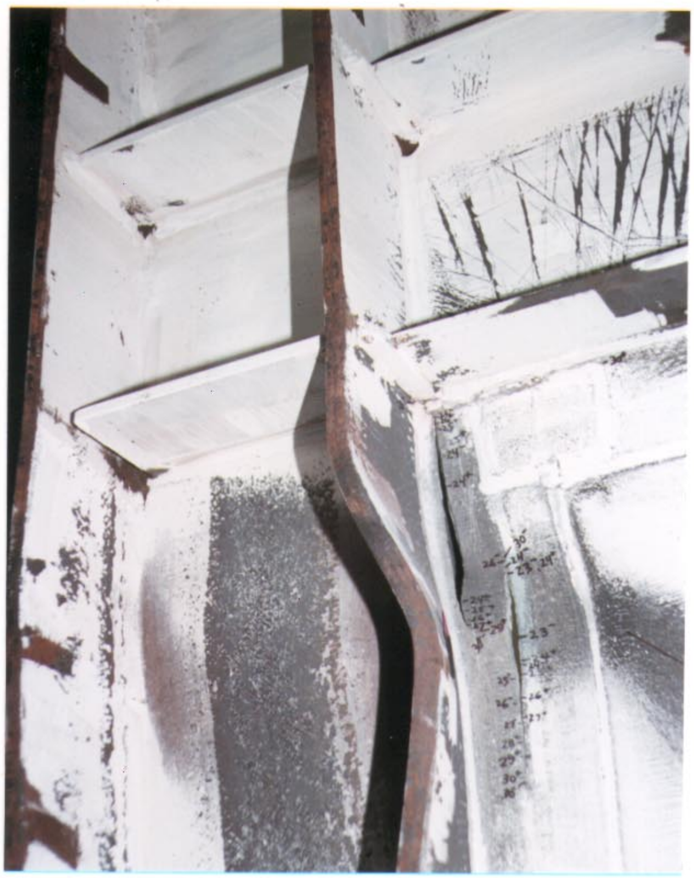

Figure 4: Tearing of shear plate at corner locations

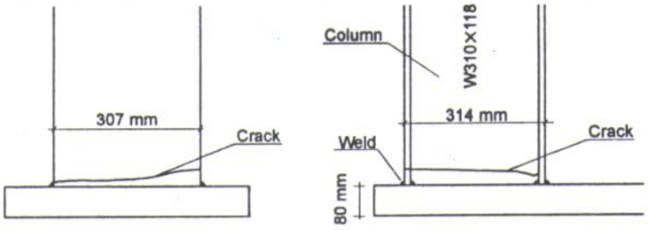

Figure 5: Crack pattern in west column

DESCRIPTION OF VIBRATION TESTS

Vibration tests were performed for two major reasons: (i) to determine the nature and extent of the vibration response levels in the frame and (ii) to verify the analytical model and its predictions. There are two types of vibration tests in common use, namely ambient and forced vibration methods. In the ambient vibration method, vibration responses are measured due to unknown forces (e.g. wind, machine operation, etc.) and the input motion to the structure is assumed to resemble "white noise" with a full frequency spectrum. In the forced vibration method, a structure is vibrated with known excitation. This type of test is generally conducted under more closely-controlled conditions than the former and consequently yields more accurate and detailed information. Impact tests are one type of forced vibration method, which have been used to measure the dynamic response of small structures. The location and direction of impacts have to be determined carefully, however, so that the required modes of vibration are excited sufficiently for accurate measurements. Other methods use rotational shakers, rockets or hydrodynamically controlled masses.

Both types of vibration tests were performed on the shear wall frame. Ambient vibration tests were performed first, followed by the impact tests, which were used for result validation purposes. The first phase of vibration measurements was performed on the undamaged specimen on a weekend when no other activities were going on in the laboratory and the only major source of excitation was the main air circulation fan. The second set of tests was performed during a weekday, when the laboratory was in normal operation, but no heavy testing was going on. A preliminary dynamic analysis using the commercial program SAP90 (Habibullah, 1990) was performed to gain basic knowledge about the fundamental frequencies and mode shapes of the steel plate shear wall frame. This information was used in the planning process to determine sensor locations and test sequence.

Ambient Vibration Tests

Eight strong motion accelerometers were used for the measurement of motions, which required four setups for the ambient vibration tests. Figure 6 shows the location and direction of the ambient vibration measurements along the height of the shear wall frame. Three reference sensors were used during the ambient vibration test, in the longitudinal, transverse and vertical directions. The remaining five accelerometers were moved to different locations for each test setup. Since the reference sensors were to be used to normalize the entire data set, having them located at a position of large relative motion was important. Furthermore, their location was assigned based on the approximate mode shapes of the structure and to ensure that the structure would exhibit motion at that particular location for all the natural frequencies of interest. The top left corner of the specimen was selected as the location for the reference sensors, as shown in figure 6. The data was collected for a total of eleven stations (numbered 0 to 10 in figure 6) in the longitudinal, transverse and vertical directions. Sensor 10 was attached to the floor about 3m away from the specimen to measure the free field vibrations. At each station, the calibrations of the accelerometers were verified before each test.

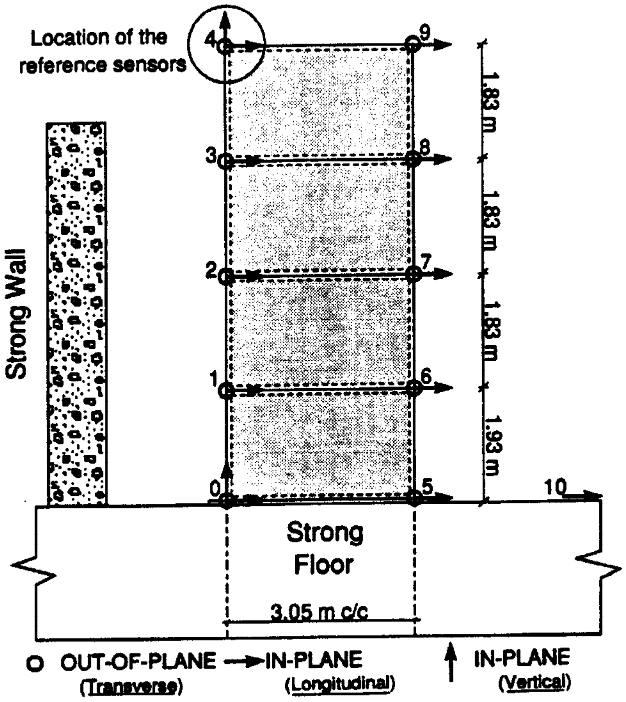

Figure 6: Sensor locations on test frame

Impact Tests

Impact tests were performed by an impulse hammer that was instrumented with an integral piezoelectric force sensor to measure the applied force. Two sets of hammer impacts were applied on the specimen at two different locations (locations 2 and 4 in figure 6) and only in the longitudinal direction. Four consecutive hammer blows were struck at each location with interval of approximately 16 seconds for a total of 64 seconds. The impacts at the top storey of the frame were applied to excite the frame mainly in the first mode, while impacts at the second storey were meant to induce some energy for the second mode of vibration.

NATURAL FREQUENCIES AND MODE SHAPES OF THE SPECIMEN

Responses of the steel plate shear wall specimen for both impact and ambient vibration tests were measured in the two orthogonal directions: longitudinal and transverse. The natural frequencies and mode shapes of the specimen were obtained from a frequency domain analysis of the signals for the two test stages: undamaged and damaged. Since natural frequencies are proportional to the square root of stiffness, any structural degradation would result in a global decrease in natural frequencies. The frequency-domain relationships of the acceleration data recorded at each phase of the vibration tests were studied in detail.

The Averaged Normalized Power Spectral Density (ANPSD) plots of the acceleration time series were computed using the program V2 (Felber, 1993). The longitudinal records were used to compute the longitudinal ANPSD while the transverse ANPSD was evaluated using the transverse records. The torsional ANPSD was computed by subtracting the time histories of two accelerometers in the same horizontal level but at different sides of the frame. The mode shapes of the frame in the transverse and longitudinal directions are shown in Figure 7.
The frequency response function (FRF) was used to determine the natural frequencies of the frame. The response of the longitudinal sensors at the top left corner and at the left side of the second storey were taken as the output signals for the hammer blows. The hammer impulse was used as the input signal.

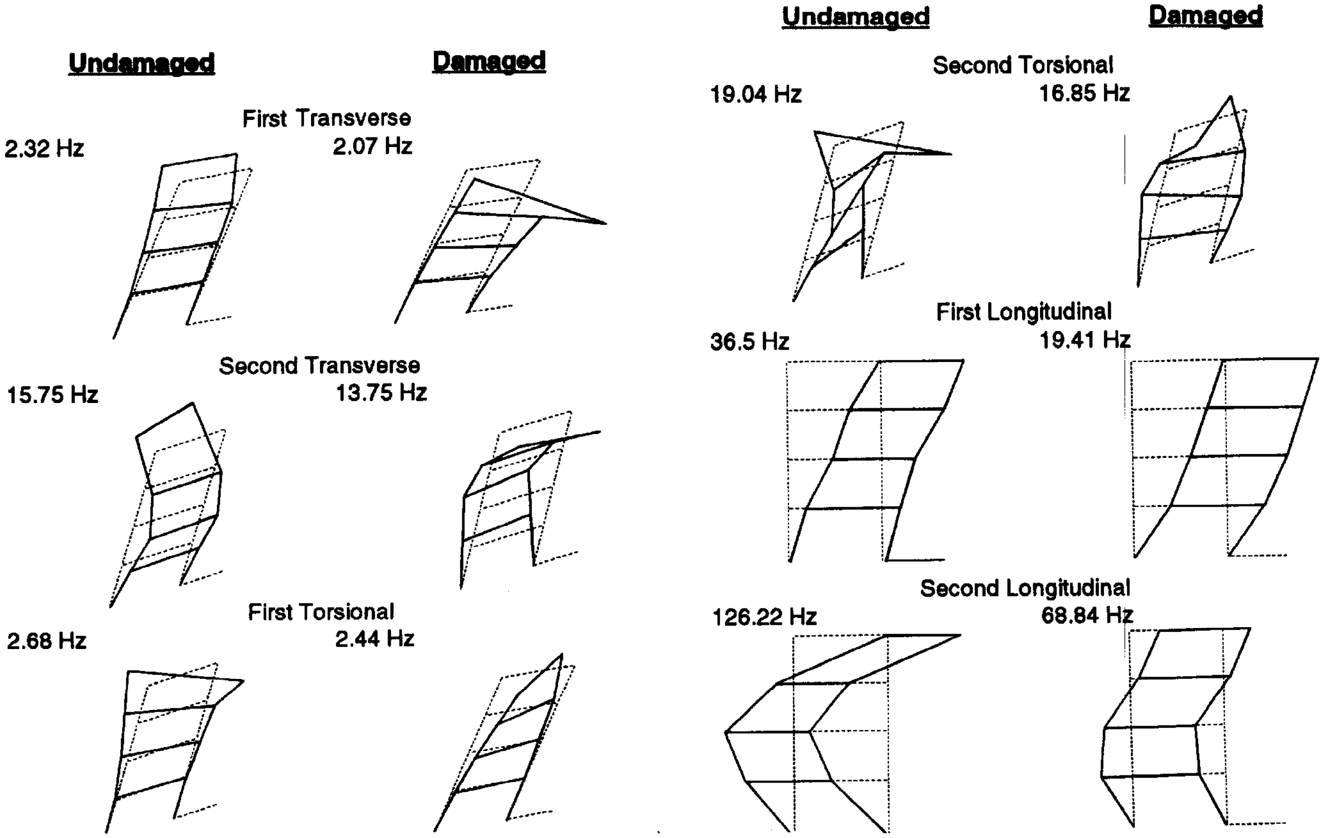

Figure 7: Mode shapes of undamaged and damaged frame

RESULTS

A computer modal analysis of the undamaged steel plate shear wall frame using the commercial program SAP90 was performed to give an idea about the possible natural frequencies of the specimen. The summary of the natural frequencies detected from the present ambient vibration test in comparison with the computer results are presented in Table 1. No attempt of correlation between the theoretical and experimental values was made.

As indicated in Table 1, substantial reductions in the natural frequencies of the infilled frame were observed in the longitudinal direction. This is due to the loss of stiffness caused by major structural damage in the direction of load application. Since the natural frequency squared is proportional to the structure's stiffness, a 50% reduction in the natural longitudinal frequency could well represent as much as 75% structural degradation (both axial and bending rigidities) in that direction. On the other hand, an averaged 10% reduction in the natural frequency in the transverse direction indicates only a 23% stiffness decay in that direction.

For the purpose of comparison, an elastic dynamic analysis of the frame with the bottom shear panel removed and the column bases pinned, yielded a natural frequency of 15.6 Hz, while the same model with fixed column bases had a natural frequency of 25.4 Hz. This indicates that the damage in the bottom panel and in the column contributed mostly to the decrease in frequency. In the transverse direction the crack in the column was the major cause for the softening effect. Although the crack severely impeded the bending strength, the stiffness was not affected to the same extent.

Direction of the Mode Shape	Frequency (Hz)					
	(SAP90 Analysis)	(Ambient vibration testing)			Impact testing	
	Undamaged	Undamaged	Damaged	Reduction	Undamaged	Damaged
First Transverse	2.87	2.32	2.07	10.78%	---	---
First Transverse-Torsional	3.72	2.68	2.44	8.95%	---	---
Second Transverse	13.43	15.75	13.75	12.7%	---	---
Second Transverse-Torsional	19.88	19.04	16.85	11.5%	---	---
First Longitudinal	**40.8**	**36.5**	**19.41**	**46.82%**	**37.35**	**19.35**
Third Transverse	36.37	61.89	53.22	14%	---	---
Third Transverse-Torsional	Not	52.61	50.05	4.86%	---	---
Fourth Transverse	36.37	111.08	98.39	11.42%	---	---
Fourth Transverse-Torsional	Not	97.29	90.21	7.27%	---	---
Second Longitudinal	**126**	**126.22**	**68.84**	**45.49%**	**126.5**	**68.48**

Table 1: Comparison of measured and calculated natural frequencies for the damaged and undamaged frame

Table 2 compares the first four modes of out-of-plane vibration of the infill plate with those obtained from the SAP90 computer model. No attempt was made to match the results. The experimental results indicate that the plate is stiffer in the out-of-plane motion than the numerical model. This extra stiffness could be attributed to the effect of the fish plates that are used to connect the infill panels to the boundary members. The fish plates are 100 mm wide and 6 mm thick and are welded to the beams and columns by means of fillet welds.

CONCLUSIONS

Experimental vibration measurements were successfully applied to determine the dynamic characteristics of a four-storey one-bay half-scale steel plate shear wall specimen using data obtained from ambient vibration and impact tests. Experimental data was analyzed to identify the natural frequencies and mode shapes of the shear wall specimen before and after the application of external loading. The averaged normalized power spectral density and frequency response functions were computed to identify the transverse and longitudinal modes, which were used to determine the influence of damage on the vibration characteristics of the frame. Good agreement was achieved between experimental and analytical results of the undamaged frame. The substantial difference in lateral and longitudinal frequencies permitted a clear separation of the longitudinal vibration modes, which were determined by both ambient and impact measurements. The transverse and torsional modes, however, had almost identical frequencies and coupling of the modes could be observed.

The pronounced decrease in natural frequency was observed for the in-plane modes of vibration as a result of the crack in the one column and damage to the shear plate in the bottom storey. The transverse (out-of-plane) mode shapes clearly show a shift from symmetric to unsymmetric motion, accompanied by a moderate decrease in natural frequency. A small decrease in natural frequency of the buckled infill plate in the out-of-plane direction could be attributed to tearing and crumpling of the plate.

The impact test was the fastest and easiest way to identify the first and second fundamental frequencies and mode shapes of the frame and also produced more reliable results, as the true input-output conditions were clearly defined. The ambient vibration test did not provide results as clear as for the impact tests, but yielded information on a larger amount of vibrational modes. This method is more appropriate for full scale large structures where impact methods would not excite the structure sufficiently or cause considerable local damage.

Vibrational measurements have been shown to be an efficient method of identifying damage to a steel frame in two ways, namely (i) by comparing pre-event with post-event dynamic characteristics, such as frequencies and mode shapes, and (ii) by observing asymmetrical features in the mode shapes for a regular building for which no pre-event measurements exist.

Mode Shape	Frequency (Hz)		
	(SAP90 Analysis)	(Impact testing)	
	Undamaged	Undamaged	Damaged
First	11.08	15.75	13.95
Second	15.44	19.21	16.97
Third	23.25	24.88	22.28
Fourth	27.82	28.37	24.96

Table 4: Comparison of the measured and computed natural frequencies of the infill plates

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