Correlation between Pseudo-Dynamic and Shake Table Test on Steel Truss Moment Frames with Hysteretic Dampers

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SUMMARY:

Experimental research is the most effective approach for determining the nonlinear behaviour of a structure or any of its critical components. Pseudo-Dynamic (PsD) test method carried out on test specimens of scaled models offer advantages of relative ease and low cost of testing. A correlation between PsD and Shake Table (ST) test had been carried out to examine the suitability of the PsD test in determining the seismic performance of hysteretic dampers in the form of Aluminium Shear Yielding Device (Al-SYD) in truss moment frames (TMFs). A wide range of Taft motions ranging from PGA 0.15g to 2.55g were used to perform the tests. Apart from some discrepancies, experimental studies showed the efficacy of PsD tests in simulating the seismic loads and the seismic response of the structure and the results were in good resemblance with those obtained from the ST test. Satisfactory performance of Al-SYDs was observed in improving the seismic performance of TMFs.

Keywords: Pseudo-dynamic test, Shake table testing, Aluminium shear link, Hysteretic damper

1. INTRODUCTION

For aseismic design of structures, the designers have to take into considerations the assumptions and properties like the nonlinear behaviour of its critical components or dampers and the parameters, like seismic performance factors (ductility, overstrength factor, etc.) provided by various codes. Considering the importance of the above mentioned factors, experimental research seems to be the most reliable and effective method for the assessment of the nonlinear behaviour of a structure as a whole or of any critical components. Many numerical methods and nonlinear analysis softwares have been developed for determining the seismic behaviour of structures. But there are some components whose behaviour cannot be predicted or modelled satisfactorily. Therefore, by experimentation one can understand the behaviour of critical components and can also develop new systems or modify the existing ones to improve the seismic performance of structures.

The most appropriate way to determine the seismic worthiness of the structures is to subject the prototype structure to the actual earthquake motion (Aktan, 1986). Various static and dynamic experimental methods are available which can be used for the assessment of seismic behaviour of structures. Some of the experimental techniques available are quasi-static (QS) load testing, shake table (ST) testing and pseudo dynamic (PsD) test method. The ST testing is the most realistic experimental method in determining the dynamic behaviour of a structure. However, the dimension, capacity and instrumentation cost of shake tables does not make the full scale testing feasible. Taking into account the realism and limitations of ST testing, the PsD Test method, also known as Online Test method was developed. Further, advantage in terms of cost and time can be achieved if small scaled models are used for PsD tests.

The objective of the present study is to calibrate the adequacy and efficacy of the PsD test on scaled models. For this purpose, correlation study was performed between PsD and ST tests on steel Truss Moment Frame (TMF) with hysteretic dampers as Aluminium Shear Yielding Device (Al-SYD).

2. PSEUDO-DYNAMIC (PsD) TEST METHOD

PsD test method (also referred as Online Testing) is an experimental online computer simulation technique to evaluate the seismic performance of a structure. It is the combination of the experimental technique and numerical analysis (Mahin and Shing, 1984). The original concept of this test was proposed in late 1960s (Hakuno et al., 1969) and was developed about thirty five years ago in Japan by Takanashi et al. (1975). Since then many research studies have been carried out to make the method more efficient and accurate. The governing equation of motion for any structure under dynamic excitation is:

$$[m]{\ddot{x}} + [c]{\dot{x}} + [k]{x} = {f(t)}$$
(2.1)

where, [m] is the mass matrix, [c] is the viscous damping matrix, [k] is the stiffness matrix and $\{f(t)\}$ is the external force vector. During an excitation a structure generally exhibit a non-linear behaviour and analytical solutions of such equation of motion can only be determined when [m], [c] and [k] remain constant. However, the numerical simulations used in various softwares rely on certain hysteretic rules to trace the changing stiffness. In case of PsD test method governing equation of motion becomes:

$$[m]{\ddot{x}} + [c]{\dot{x}} + {R(t)} = {f(t)}$$
(2.2)

where, [m] and [c] are same as above, $\{R(t)\}$ is the restoring force vector and $\{f(t)\}$ is the external force vector. The PsD test method accounts for the non-linear behaviour of the structure directly through experimentally measured restoring forces. In PsD method the structure is first discretized to finite number of degree of freedom (DOFs) along with system of actuators applied to these DOFs. By discretization, the equation of motion can be represented by second order ordinary differential equations. Further, with the help of this method one can generate the hysteretic behaviour of different important components of a structure which can play a significant role under a seismic event. When the specimen undergoes non-linear hysteretic behaviour the energy dissipation is automatically taken into account and so the analytically prescribed viscous damping which is difficult to determine accurately becomes less critical (Mahin et al., 1989).

2.1. Methodology

During test, the governing equation of motion is solved by a step by step numerical integration method. For the test and the numerical method, the inertial and the viscous damping characteristics are analytically prescribed. To simulate the seismic response of the structure, a ground motion is provided as an input to the system (idealized mathematical model in computer). With the help of a program the displacement is calculated at a small time step which almost resembles the same displacement which the structure will be subjected during a seismic excitation. The calculated displacement is imposed on the structure which is measured by load transducers. The measured forces and other important measurements are fed back to the computer as voltage signals and are used further to calculate the next displacement to be imposed on the structure.

2.1.1. Experimental Errors

For executing reliable pseudo-dynamic tests, the instrumentations used should be of high precision. The difference in displacement applied by the actuator and calculated displacement generates error in the displacement control, which in turn is reflected in measured restoring forces. These errors keep on accumulating as the step by step numerical integration scheme proceeds (Mahin and Shing, 1984; Takanashi and Nakashima, 1987). Many studies have been carried out to minimize the errors generated. Many numerical algorithms have been proposed in various studies so as to reduce the tolerance for these errors. Summaries of these studies are provided in Takanashi and Nakashima, 1987; Mahin et al., 1989; Shing and Mahin, 1990; Chang, 2002).

2.1.2. Numerical Method

A suitable numerical integration method is required to solve the equation of motion step by step. In PsD test the previous step data will be used to calculate the current step data and thus the error induced in any time step will be propagated to the remaining time steps (Shing and Mahin, 1990). It is, therefore, important to select an appropriate integration method to obtain reliable PsD test results. In the present study a PsD software developed by MTS systems in co-operation with the University of Colorado, Boulder is used (MTS Systems Corporation Manual, 2005). The program developed uses HHT- α Method, shown in Eqn. 2.3, 2.4 and 2.5, for step by step time integration of the equation of motion corresponding to the restoring force measured during the test.

$$[m]\{\ddot{x}_{i+1}\} + (1+\alpha)[c]\{\dot{x}_{i+1}\} - \alpha[c]\{\dot{x}_i\} + (1+\alpha)\{r_{i+1}\} - \alpha\{r_i\} = (1+\alpha)\{f_{i+1}\} - \alpha\{f_i\}$$
(2.3)

$$\{x_{i+1}\} = \{x_i\} + \Delta t \{\dot{x}_i\} + \Delta t^2 \left[\left(\frac{1}{2} - \beta\right) \{\ddot{x}_i\} + \beta \{\ddot{x}_{i+1}\} \right]$$
(2.4)

$$\{\dot{x}_{i+1}\} = \{\dot{x}_i\} + \Delta t \Big[(1-\gamma) \{\ddot{x}_i\} + \gamma \{\ddot{x}_{i+1}\} \Big]$$
(2.5)

where [m], [c], $\{\ddot{x}_i\}$, $\{\dot{x}_i\}$ and $\{x_i\}$ are the same as stated above; $\{r_i\} = [k_i]\{x_i\}$ is the restoring nodal force vector corresponding to nodal displacement vector $\{x_i\}$; and $\{f_i\}$ is the external force vector.

3. SHAKE TABLE TEST METHOD

Shake table test is the most realistic experimental method for determining the dynamic response of structures as per the equation of motion.

$$[m]\{\ddot{x}\} + [c]\{\dot{x}\} + [k]\{x\} = -[m]\{\ddot{x}_g\}$$
(3.1)

where $\{\ddot{x}_g\}$ is the ground acceleration acting on the system, rest of the variables have their usual meaning. In the shake table test the structure is fixed to the rigid platform which is excited with servo-hydraulic actuators to simulate the given ground motion, \ddot{x}_g in real time. The development of advanced technologies has made possible the installation of large, multi-degree of freedom shaking-tables, which are capable of driving large masses of prototype-sized structures with a high degree of accuracy of reproduction of the seismic ground motions. However, these testing facilities are rare because of the high costs involved in installation, operation, and construction and testing of full-scale prototype structures. Therefore, due to limitations on capacity and size of the table, reduced scale models are mostly used for testing of specimens in many laboratories.

3.1 Reduced Scale Modelling

In present study the setup was fabricated according to the size and weight limit of the shake table at IIT Kanpur (Sinha and Rai, 2009). Length scale ratio of 1:6 was chosen to accommodate the specimen on the shake table. An acceleration scale of 3 was considered to reduce the imposed load on the model for simulation of similar stresses in columns and for adequate dynamic simulation, time and frequency ratios were modified according to the applicable similitude relations. The similitude laws and the scale ratios used for defining the model are shown in Table 3.1.

Quantity	Dimensions	Scale Ratio	Values
Length	L	S	1/6
Mass	М	ρs^3	1/108
Acceleration	LT ⁻²	<i>S</i> _a	3
Time	Т	s ^{0.5}	$1/\sqrt{18}$
Force	LMT ⁻²	s^2	1/36
Frequency	T ⁻¹	$1/s^{0.5}$	$\sqrt{18}$

Table 3.1. Model scaling requirements in present study

4. PROTOTYPE BUILDING

The prototype building is a single storey large span industrial building, 90 m long (9 bays @ 10 m) in the E-W direction and 27 m long (3 bays @ 9 m) in N-S direction with accessible roof, located in seismic zone V on the soil profile Type II (stiff soil) as per IS 1893 (Part-1) (BIS 2002). The height of the building is 9.5 m. The building has eight lateral load resisting frames in N-S direction installed with shear links. The plan view of the building and the elevation along N-S direction of the building are shown in Fig. 4.1.



Figure 4.1 Single storey large span industrial building (Sachan & Rai, 2012)

The building carried a dead load of 0.64 kN/m^2 on roof and 0.4 kN/m^2 due to walls, while a live load of 1.5 kN/m^2 . Only the middle bay installed with shear link was designed to resist seismic loads while rest of the frames was designed to resist gravity loads only. The total seismic weight was calculated as 2887 kN as per IS 1893 (2002). The fundamental period of the structure was determined as 0.46 s. For designing, the strong column – weak girder philosophy was used such that all the nonlinear activities were limited to shear links only. The frame was designed as per IS 800 [BIS, 2007]. The steel members of the frame designed are shown in Table 4.1. The maximum compressive or tensile forces developed in the bottom chords of the truss due to various load cases was the design shear force for the shear links. For the determination of lateral load due to earthquake, the equivalent viscous damping of the structure was assumed to be 5% and the response reduction factor was taken as 5. Table 4.2 shows the dimensions of the designed shear link.

Members	Sections Used
Columns	ISMB 500 @ 86.9kg/m
Chords	2 ISA 65×65×8 @ 7.7kg/m
Diagonals	ISA 100×100×10 @ 14.9kg/m
Verticals	ISA 75×75×10 @ 11kg/m

Table 4.1. Members of Al-SYD TMF designed to resist lateral forces

Design Moment (kNm)	Design Shear Force (kN)	Web area Required (mm ²⁾	Web area provided (mm ²⁾	Dimensions (mm)		
307.84	205.22	2360	2400	l_w	t_w	d
507.04				400	6	180

 l_w = web length; t_w = web thickness; d = Depth of shear link

4.1. Specimen

The details of test set-up are shown in Fig. 4.2. The shear links were placed at the end of the bottom chords, this saved the floor area otherwise occupied in installing the dampers. The specimen was first tested on shake table and then the same specimen was used for PsD test after replacing the damaged shear links. Various steel sections used in fabricating the structural members of the specimen are provided in Table 4.3 along with their yield and ultimate strength.



Figure 4.2 Overall test setup and arrangement of shear links in the TMF

Truss Frame	Section	Yield Strength (MPa)	Ultimate Strength (MPa)	
Chords (upper and lower)	2 Angles 25×25×1.5 mm	385	502	
Diagonals	Angle 18×18×1.6 mm	395	519	
Verticals	SHS 15×15×1.17 mm	480	556	
Columns	ISLB 75 @ 6.1 kg/m	324	468	

Table 4.3. Various sections used and their yield and ultimate strength

4.2. Aluminium Shear Yielding Damper (Al-SYD)

Al-SYDs were fabricated by machining a 50×50 mm block of aluminium 6063-T6 alloy. Fig. 4.3 shows the dimensions of the shear link required for the testing of the scaled model. Table 4.4 shows the average dimension of the actual fabricated shear links for both the tests. The slight difference in the dimensions of the shear links was observed due to the fact that for both tests the shear links were manufactured using vertical milling machine and despite the proper care the web thickness of 1.3 mm had an error of 9% and 4% for shear links used in ST test and PsD test, respectively. As a result the average web area of shear links used in the PsD test was 0.87 times to that used in ST test. After fabrication, the shear links were annealed to soften work hardened and heat treated alloy structures to relieve internal stresses. Fig. 4.4 shows the tensile coupon test results of both annealed and unannealed aluminium coupons.



Figure 4.3 Required dimensions of shear link (Sachan, 2011)

Test	Avg. Web Thickness (mm)	Avg. Area (mm ²)	Yield Stress (MPa)	Ultimate Stress (MPa)	Yield Force (kN)	Ultimate Force (kN)
PsD	1.25	53.64	40	85	1.29	4.2
ST	1.42	61.17	52	116	1.84	6.0

Table 4.4. Comparison of specifications and mechanical properties of the shear link



Figure 4.4 Stress-Strain curves for (a) unannealed aluminium coupons; and (b) annealed aluminium coupons

5. EXPERIMENTAL RESULTS

For dynamic loading, TaftN21E component of the 1952 Kern County earthquake (PGA 0.156*g*) was used. Taft motion when scaled to 0.20*g* closely matched with the design response spectra of IS 1893 (2000). The total length of the original Taft motion is 54.16 s and for laboratory test of Al-SYD TMF the Taft motion was reduced to 12.76 s. The dynamic characteristics of the frame, such as fundamental frequency and damping, were evaluated by a forced vibration test. The frequency content of the obtained time history was evaluated using Fast Fourier Transform (FFT). The fundamental frequency of Al-SYD TMF for the PsD test was 3.61 Hz.

5.1. Al-SYD TMF Behaviour

The Taft ground motion of increasing PGA level from 0.15g to 2.55g (25% to 425% of the DBE) in case of PsD test and from 0.15g to 2.25g (25% to 375% of the DBE) in case of ST test was applied on the test frame. Aluminium shear links are less sensitive to the strain rate, the slow speed of the PsD test acted as an advantage in observing the behaviour of the test frame closely (Rai and Wallace, 1998). The motion was applied at the PGA level of 0.15g and up to 0.90g in a sequence of increasing PGA and no buckling was observed in any of the four shear links in both ST and PsD test. The onset of the buckling in the shear links was observed at Taft motion with PGA 1.35g (225% DBE). The tearing occurred simultaneously in all the four shear links. Figs. 5.1 and 5.2 shows the deformed shear link at PGA 1.35g and at the conclusion of the PsD and ST tests, respectively.

4.2. Correlation of Base Shear

The Al-SYD TMF can be idealized as a single DOF structure and the resisting force generated in the structure after the application of the displacement is the same as base shear imposed on the structure. The maximum base shear values observed were 4.51 kN and 3.89 kN at 1.65g PGA level for both ST and PsD test, respectively. The base shear obtained from ST test are higher than PsD test because the web thickness of the shear links used in ST test was larger as compared to the web thickness of shear links used in PsD tests. The comparison of the specifications and mechanical properties of the shear links used for the tests are shown in Table 4.4. The comparison of the base shear by both PsD test and

ST test is shown in Fig. 5.3(a). The base shear values obtained from shake table test were scaled by factor 0.87 to account for the difference in thicknesses of shear links used in both tests. The scaled base shear values match closely with PsD test values and thus depict the reliability of PsD test. The peak base shear obtained from both tests at each PGA level (DBE level) is listed in Table 5.2.



Figure 5.1 Comparison of deformation in shear links at PGA 1.35g (225% DBE)



Figure 5.2 Comparison of deformation in shear links at the conclusion ST (PGA 2.25g) and PsD (PGA 2.55g)

5.3. Correlation of Peak Displacement

The displacement response is obtained from the PsD test results by minimizing the errors if occurred. Both PsD and ST test results shows linear increase in drift of the structure upto Taft motion with PGA 0.90g. However, for large PGA levels, the drift increases at a slower rate due to the onset of inelastic activities in the shear links. The comparison of the maximum displacement by both PsD test and ST test is shown in Fig. 5.3(b). The maximum roof displacement obtained from both tests is listed in Table 5.2. Fig. 5.4 shows displacement time history for different Taft intensities. Difference in the peak displacements was observed between PsD and ST test, which was mainly due to the small difference in specimen dimensions. In the ST test, the web thickness of shear links used was slightly different among them due to which the lateral stiffness was not same in both frames and, therefore, the onset of inelastic activities such as buckling and tearing of webs did not occur simultaneously. While in case of the PsD test, a proper care was taken in maintaining the thickness of the shear links and tearing of all the four shear links occurred simultaneously at PGA level of 2.55g.



Figure 5.3 Comparison of (a) Base Shear, and (b) Roof Displacement; of Al-SYD TMF for various intensities of ground motion obtained by PsD test and ST test

SI	Toft DCA (g)	Base Shear (kN)			Maximum Displacement (mm)		
No.	io. (% DBE) PsD Test		ST Test	Ratio (PsD/ST)	PsD Test	ST Test	Ratio (PsD/ST)
1	0.15 (25)	0.74	1.14	0.65	2.6	3.9	0.67
2	0.30 (50)	1.42	1.91	0.74	5.3	6.7	0.79
3	0.45 (75)	2.05	2.33	0.87	7.7	9.6	0.80
4	0.90 (150)	2.9	3.65	0.79	16.5	20.6	0.77
5	1.35 (225)	3.72	4.38	0.85	25.9	33.8	0.76
6	1.50 (250)	3.81	4.47	0.85	28.2	37.3	0.75
7	1.65 (275)	3.89	4.51	0.86	30.6	40.9	0.73
8	1.80 (300)	3.83	4.49	0.85	32.1	44.08	0.75
9	1.95 (325)	3.76	4.18	0.89	33.5	44.8	0.66
10	2.10 (350)	3.82	3.90	0.97	33.9	51.6	0.68
11	2.25 (375)	3.85	3.49	1.1	35.8	52.4	
12	2.40 (400)	3.77			37.1		
13	2.55 (425)	3.49			36.8		

Table 5.2. Comparison of Maximum Base Shear and Displacement obtained from PsD and ST test

5.4. Correlation of Acceleration Response

The comparison of peak roof acceleration obtained from PsD test and scaled ST test is shown in Fig. 5.5(a). The peak acceleration values in PsD test were determined by dividing the base shear values with roof mass. The peak roof acceleration observed from both PsD and ST test showed close match upto 1.95g, however, at higher PGA levels the variation was primarily due to onset of buckling and tearing of shear link in these tests at different PGA levels. The peak roof acceleration increased linearly upto PGA 0.45g and 0.30g in both PsD and ST test, respectively. The increasing trend was observed up to Taft with PGA 1.65g and the corresponding peak value was found to be around 0.63g. With initiation of inelastic deformations, the rate of increase of peak roof acceleration gradually diminishes and lower inertia forces were transferred to the structure. Therefore, it can be concluded that Al-SYD is very effective in reducing the forces transferred to the structure due to its excellent damping and energy dissipation characteristics.

5.5. Correlation of Energy Dissipation

The energy dissipation by the structure subjected to a particular ground motion is calculated as the area enclosed by the hysteresis curve which is plotted between force and displacement. Due to the smaller

base shear in the PsD test, the hysteretic area or energy dissipated in the PsD test was smaller as compared to that obtained from the ST test. The total energy dissipation observed from PsD and ST test is compared in Fig. 5.5(b). In both PsD and ST tests the total dissipated energy showed increasing trend with the PGA level, however, during shake table test the energy dissipation saturated after 1.65g PGA due to buckling and tearing of shear links.



Figure 5.4 Displacement time history comparison for different Taft intensities obtained from PsD and ST test



Figure 5.5 Comparison of (a) Peak Roof Acceleration, and (b) Energy dissipation; of Al-SYD TMF for various intensities of ground motion obtained by PsD test and ST test

6. CONCLUSIONS

The PsD test proved to be a reliable, informative and economical experimental technique for small scale model specimens. Due to its slow testing rate the behaviour of the structure can be closely observed. Its use for testing of small scale specimens lead to further reduction in costs and overall effort. Satisfactory performance of Al-SYD TMF was observed for the PsD test and the results were in good resemblance with the ST test. The Al-SYD TMF in the PsD test attracted less base shear due to the small difference in the size of the shear links. The average ratio of base shear obtained from the PsD and ST test. This shows the efficacy of PsD tests in simulating the seismic response of the structures, especially the overall behaviour, as well as force and acceleration response quantities. However, some difference in peak displacements was observed which was partly due to slight difference in the web thickness and sequence of onset of yielding or buckling in both tests.

ACKNOWLEDGEMENT

The financial support provided by the Council of Scientific and Industrial Research, Ministry of Science and Technology, Government of India, New Delhi, is gratefully acknowledged. Additional support from the Poonam & Prabhu Goel Foundation at IIT Kanpur for research and outreach activities in earthquake engineering is greatly appreciated. The authors greatly appreciate the help provided by Dr. K K Bajpai and Vaibhav Singhal in conducting the experimental work and Mr Dhruv Kumar for quality work in specimen fabrication.

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