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DEVELOPMENT OF AN ON-LINE CONTROL BASED ON CONVENTIONAL PSEUDO-DYNAMIC TESTING METHOD

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Abstract

In Peru, the experimental behavior of structural systems under seismic loads is, without doubt, a field of study that requires an extensive research. Thus, in the Laboratory of Structures of CISMID, it has been testing and researching full-scale specimens under cyclic quasi-static loads and scaled specimens under seismic dynamic motion of various types of materials such as reinforced concrete, masonry, steel, and wood. On the other hand, it is known that the seismic response for scaled tests is not as reliable as the seismic response for real-scale tests. Due to the lack of devices which can lead dynamic tests of real scale specimens like high capacity shaking table or dynamic actuators, there is a necessity to develop a testing method to understand the experimental seismic behavior of a full-scale structure by using an online control of static hydraulic actuators. The Pseudo-dynamic testing technique (the online test) has been accepted, applied and improved by many researchers in the last decades around the world. However, in Peru, it is a relatively new experimental method to simulate the seismic response of a full-scale structure. This research aims to develop and try out a conventional Pseudo-dynamic test closed-control algorithm by employing the Newmark explicit integration method. The Pseudo-dynamic testing procedure, the automatic control criteria and the different sources of error effects are described in this report. Moreover, the general considerations in the analytical seismic response estimation with Newmark explicit integration method instead of an implicit integration method are discussed. A free vibration test was carried out to estimate the dynamic properties such as the natural frequency and the inherent damping of the specimens that will be Pseudo-dynamic tested. The natural vibration frequency will be used to determine the integration time interval for the correct convergence and numerical stability of the Newmark method. Likewise, the inherent damping of the specimen will be an input constant variable to solve the motion differential equation during the test. In order to verify and calibrate the Pseudo-dynamic test closed-control algorithm, two steel columns have been tested by using the record of Lima earthquake in 1974 as input. The rate that indicates the relationship between testing response speed with the real response speed was calculated. Finally, a comparison between the experimental seismic response of specimens and the analytical seismic response by using the STERA3D software is performed in order to verify the validity of the testing method. A correct correlation between experimental and theoretical results has been founded in this research.

Keywords: On-line test, Pseudo-dynamic method, full-scale specimen, quasi-static load.

1. Introduction

The structural behavior under seismic loads is an area of considerable interest to designers and researchers involved in the earthquake engineering. However, the strict analytical estimation of the inelastic seismic behavior becomes a task with certain inaccuracy due to the inevitable and engineering mathematical simplifications and the non-linear properties uncertainty. Hence, experimental methods are commonly the most attractive and realistic way to understand properly the seismic response of structures. Currently, there are different structural testing methods like dynamic tests, cyclic loading tests, Pseudo-dynamic tests, which could be applied to full-scale specimen, reduced-scale specimen and, even to a sub-structuring specimen. Moreover, it is known that the full-scale dynamic test is probably the most realistic and reliable method to understand the seismic performance of the structural systems; however, when it comes to large weight and height specimens, this testing method require a high capacity of the loading equipment. Therefore, it becomes a non-economic alternative for the laboratories of structures. With the purpose of overcoming this economic drawback, the Pseudo-dynamic testing technique has been successfully used for large structures [1].

Many efforts in researching, originated by Hakuno et. al. [2] and Takanashi et. al. [3], achieved the reliability and the acceptance of the Pseudo-dynamic method. Thus, this experimental method has been implemented and improved successfully in the laboratories of structures of the Institute of Industrial Science of University of Tokyo, the Building Research Institute (BRI) and in other parts of Japan [1]. In the same way, in U.S.A. the implementation and the improvement of the Pseudo-dynamic testing method was started by Shing and Mahin, researchers of the Earthquake Engineering Research Center of the University of California Berkeley [4][5]. These wide research contributions promote the dissemination of the Pseudo-dynamic test method. In Europe, the researchers of European Laboratory for Structural Assessment (ELSA Laboratory) developed their own Pseudo-dynamic testing System in order to understand the seismic response of Large Structures [6].

In Peru, the Pseudo-dynamic testing method is a relatively underdeveloped experimental technique. In the Structures Laboratory of Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation (CISMID), Chunga [7] developed a control program for testing full-scale specimens by using electro-hydraulic actuators. This program was performed in a Windows 98 digital computer, however, since the growth in control technology during the last decades, the programming system and the digital computer which were used for the development of the control system have reached the technological obsolescence. For these reasons, the aim of this research is to develop and to improve a new experimental testing control system for the execution of Pseudo-dynamic Tests by using the electro-hydraulic actuators. In this manner, the research is distributed in four parts where the mathematical and experimental procedures, the control system criteria, the intrinsic and experimental error effects, and the verification of the experimental results of the Pseudo-dynamic Test were described in more detail.

2. Conventional Pseudo-dynamic Test Method

The Pseudo-dynamic technique (or also known like On-line Test) is an experimental method that adequately combines the structural analysis and the experimental testing in order to simulate the earthquake response of a structural system. In this technique, instead of directly testing the specimen under a seismic excitation at the base, the displacement response is calculated by an integration numerical method and it is replicated using electro-hydraulic actuators. The conventional Pseudo-dynamic test is referred to the original test performed by Takanashi et. al. [3] and is characterized because the load and displacement measurement instrumentation are commonly used in quasi-static loading tests. Thus, the mathematical formulation of the Pseudo-dynamic method performs a structural idealization of the specimen to a Lumped Mass mechanical model, where the analytical methods can be applied with acceptable accuracy. It is necessary to emphasize that mathematical analysis of the specimen treated as a continuous system (finite element method, for example) would be very complex and would require relatively a high computing time, which is not very convenient for the Pseudo-dynamic test. Under these assumptions, the D'Alembert Principle can be applied to formulate the matrix differential equation that governs the dynamic movement of a multi-degree of freedom (MDOF) linear system under a seismic excitation, as can be seen at Eq. (1) [8].

$$[M].\{\ddot{X}\} + [C].\{\dot{X}\} + [K].\{X\} = \{f\} \tag{2}$$

Where [M], [C] and [K] are the mass, damping and stiffness matrix; $\{\ddot{X}\}$, $\{\dot{X}\}$, $\{X\}$, the acceleration, velocity and displacement response vectors, respectively; and $\{\ddot{X}\,g\}$, the seismic excitation vector. Moreover, $[M].\{\ddot{X}\}$, $[C].\{\dot{X}\}$, $[K].\{X\}$ and $\{f\}$ can be denoted as the inertial force, the damping force, restoring force: {R}, which can be lineal or no lineal, and the excitation force, respectively.

In the experimental formulation of the Pseudo-dynamic method, the inertial force, $[M].\{\ddot{X}\}$ and the damping force, $[C].\{\dot{X}\}$, are estimated prior to the test by means of an analytical or experimental procedure; however, the restoring force, {R}, is measured directly from the test with the actuator load cell. The seismic displacement response is calculated by a step by step direct integration method, which will be described in more detail in the next section. The interaction procedure between the experimental measurements and the analytical solution of the equation of motion is possible by the continuous monitoring of the Servo-Controller feedback and the displacement transducer (LVDT). In this way, the mathematical integration gives calculated displacements at each time step that will be sent in the form of an electrical signal to the Servo-controller and quasi-statically will be imposed on the specimen by means of the electro-hydraulic actuator.

2.1 Step by Step Integration Method

The step-by-step numerical integration methods are commonly used in the On-line Tests due to the direct estimation of the displacement response by using a discretized excitation like an earthquake acceleration record. Thus, the Eq. 1 is conveniently rewritten as follows in Eq. 2 for the time step t+Δt.

$$[M].\{\ddot{X}\}^{t+\Delta t} + [C].\{\dot{X}\}^{t+\Delta t} + [K].\{X\}^{t+\Delta t} = \{f\}^{t+\Delta t} \tag{2}$$

Generally, there are two types of direct integration methods: the explicit methods and the implicit methods. The first one is when the displacement response at the time step t + Δt only depends on the conditions prior to the corresponding step. For example, the Central Difference Method is an explicit direct integration method that uses estimated values of two previous conditions for estimating the response and it has been successfully used in the On-line Tests by many researchers worldwide [1]. Then, the implicit methods would be all other methods that do not have this requirement. Although it is known that direct integration methods are approximate mathematical methods, implicit methods have a better accuracy to the true response than explicit methods, due to its extra-process corrective iteration for obtaining the response at each time step. One of the most popular implicit integration methods in structural dynamics is the Newmark methods. This method has certain assumptions that are written in Eq. 3 and Eq. 4 [8]

$$\{\dot{X}\}^{t+\Delta t} = \{\dot{X}\}^{t} + \left[(1-\delta).\{\ddot{X}\}^{t} + \delta.\{\ddot{X}\}^{t+\Delta t}\right].\Delta t \tag{3}$$

$$\{X\}^{t+\Delta t} = \{X\}^{t} + \{\dot{X}\}^{t}.\Delta t + \left[(0.5-\alpha).\{\ddot{X}\}^{t} + \alpha.\{\ddot{X}\}^{t+\Delta t}\right].\Delta t^{2} \tag{4}$$

Where, δ y α are parameters that can determine the precision and the convergence of this method characterizing the variation of the mathematical acceleration during the integration process. The value of Δt is the step of integration (which if closer to zero would have solutions closer to the true response), and the other values are equal to those mentioned above for the time step t + Δ t.

Stability and accuracy are the key for that the integration method has reliable results [4]. Accuracy is achieved as small as the chosen integration interval (Δt). However, since the Δt can be lower, a greater amount of calculated displacement targets will be provided during the test, which would result in a very long and impractical experimental assessment; and in addition, could contribute to the experimental cumulative errors [9]. On the other hand, unconditional stability can be achieved with implicit methods. Nevertheless, explicit methods have a conditionality in their stability that manifests with finite permissible limits of time interval. In the Central Difference Method, it is possible to show that the stability condition is: $w_{max} . \Delta t <= 2$ [8]. Where w_{max} is the highest modal circular frequency.

In spite of these notable advantages, implicit methods are not generally desired for applying in Pseudo-dynamic tests because to the mentioned iterative correction of its solution. Then, according to the right-hand side of Eq. (3) and (4), the term, $\{\ddot{X}\}^{t+\Delta t}$, makes Newmark methods implicit. In order to determine this value, the restoring force, $[K].\{X\}^{t+\Delta t}$, which is obtained from the Pseudo-dynamic test, must be necessarily estimated; however, for this task, the displacement $\{X\}^{t+\Delta t}$ should be applied a priori in the test. Therefore, the applying an iterative method to determine instantaneous stiffness in a nonlinear system during the test is required; moreover, these corrective operations could cause undesired unloading into the specimen during the Pseudo-dynamic testing method [5] [10].

In order to convert the Newmark method into explicit method, one can consider the value α=0 and the value δ=1/2 by eliminating the value $\{\ddot{X}\}^{t+\Delta t}$ and by achieving a suitable approach in the results. In this investigation, the authors have decided to use the explicit Newmark method due to its characteristic of estimating the structural response with dependence on the conditions of a single previous step [4]. In this way, the equations that describe this method are written in Eq. (5), (6) and (7).

$$\{X\}^{t+\Delta t} = \{X\}^{t} + \{\dot{X}\}^{t}.\Delta t + 0.5.\{\ddot{X}\}^{t}.\Delta t^{2} \quad (5)$$

$$\{\ddot{X}\}^{t+\Delta t} = ([M] + 0.5.\Delta t.[C])^{-1}.(\{f\}^{t+\Delta t} - \{R\}^{t+\Delta t} - [C].\{\dot{X}\}^{t} - 0.5.\Delta t.[C].\{\ddot{X}\}^{t}) \quad (6)$$

$$\{\dot{X}\}^{t+\Delta t} = \{\dot{X}\}^{t} + 0.5.\Delta t.(\{\ddot{X}\}^{t} + \{\ddot{X}\}^{t+\Delta t}) \quad (7)$$

2.2 Control Criteria

In this research, a close-loop displacement control algorithm is implemented in the Pseudo-dynamic Test program in order to achieve the correct measurements of computed displacement as well as experimental restoring force recorded from the displacement transducer and the load cell, respectively. The displacement control follows certain control criteria that will be described below.

In the On-Line Tests, the electro-hydraulic actuator movement is applied to the specimen continuously during the test and the restoring force is measured immediately after the transducer displacement reaches the target displacement [11]. The continuous loading procedure is illustrated in Fig. 1. The actuator motion reaches the target displacement X_{Ti} and then is directed to the next displacement X_{Ti+1}, which correspond to the time step i and i + 1, respectively. The computer program transforms the estimated displacement of the time step i into a voltage signal, $V(X_{Ti})$ by means of convertor D/A of 16 bits, which will be sent to the Servo-Controller. Then, the actuator will replicate this displacement; however, the specimen stiffness will impede the piston reaches the target displacement at the first iteration. Therefore, a close-loop displacement control would ensure the required piston movement for each time step.

An analog displacement transducer will record the deformation of the specimen in voltage of $V(X_j)$, which will be measured by the digital computer, through the convertor A/D (also of 16 bits), as a displacement X_j, by obtaining an error $e_j = X_{Ti} - X_j$. The computer will send again a new voltage: $V(X_{Ti}) + \Delta V$, where ΔV depends on the error detected e_j, according to the following expression: $\Delta V = k.\Sigma\, e_j$. Where j is the number of steps the actuator piston could take to converge monotonically to the desired value at each time step. The value of k must vary between 0 to 1, and for the algorithm proposed in this research, the value of k was 0.5 [10]. This monotonic iterative process is carried out until the measured error is less than a certain tolerance $\pm\ \varepsilon$, that will be entered into the program a priori to the test. Thereby, the first control criteria is based on this electro-hydraulic actuator continuous action. This movement must be imposed on the specimen in a monotonic manner at each time interval Δt. It means an unloading is not allowed in the displacement control process because that may produce stiffness deterioration that are not considered [4] [10]. The second criteria is referred to the displacement control. Due to the imperfect and finite resolution of the measuring instruments; and also, the data acquisition system, the target displacement could not be replicated exactly in the specimen, but will have a tolerance of error ($\pm \varepsilon$). This value depends on the sensitivity of the mechanism that measure displacement of the actuator stroke as well as displacement transducer. In this investigation, the value of ε is an input of the test program and is equal to 0.01 mm.

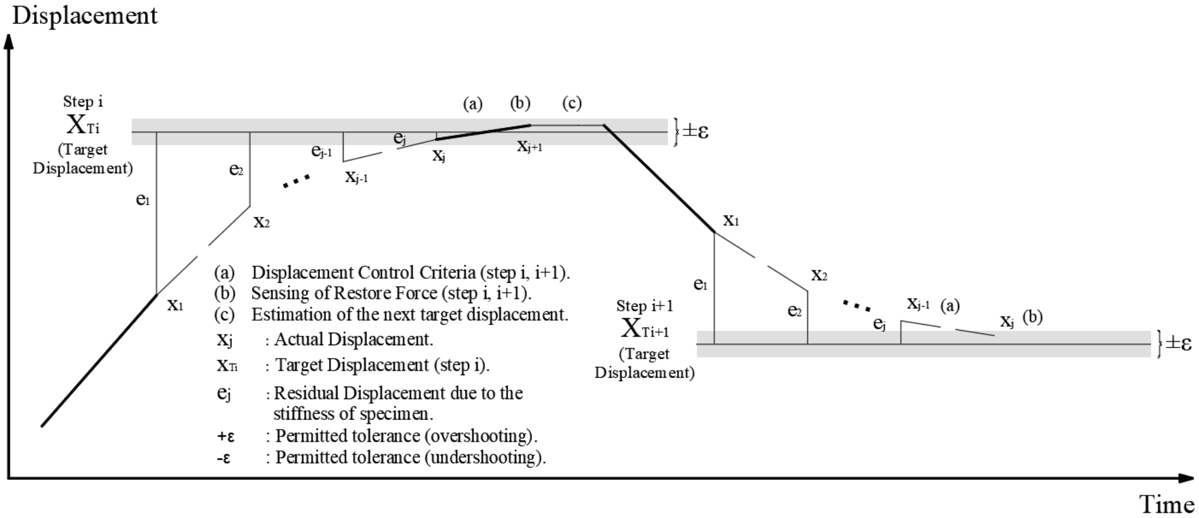


Fig. 1 – Continuous Action of the Electro-Hydraulic Actuator during the Pseudo-dynamic Test [11].

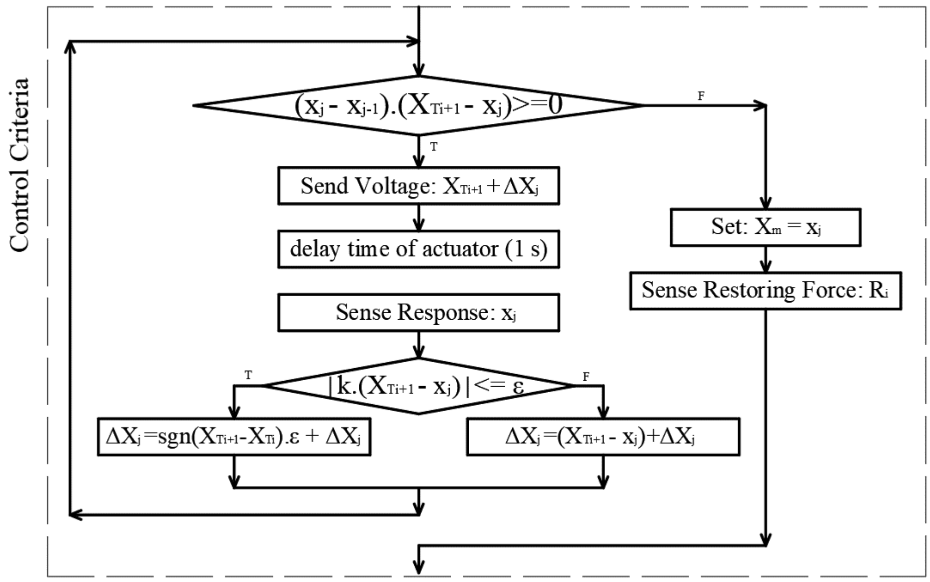


Fig. 2 – Flow Diagram of Close-Loop Displacement Control in the Pseudo-dynamic Test.

The two control criteria previously described in Fig. 1 are summarized in the control algorithm of the flow diagram of the Fig. 2. The mathematical condition that controls the movement of electro-hydraulic actuator, $(X_j\text{-}X_{j-1}).(X_{Ti+1}\text{-}X_j)$, is observed in this figure. The left-hand side term would be negative if would have any unloading in the convergence process of the control system. Similarly, the right-hand side term becomes negative if the measured displacement exceeds the target displacement. Therefore, the control condition that governs the displacement control will exit the loop when it finds at least one negative value in either of the two mathematical expressions.

3. Error in Pseudo-dynamic Testing

The capability of Pseudo-dynamic Test to simulate the seismic behavior of structural systems is greater compared with other types of tests like a dynamic Shaking Table Test. This is because the mechanisms that apply the load to the specimen, such as electro-hydraulic actuators, do not act directly on the base where the entire weight of the structure is supported, but instead replicate the relative displacement movement in the degrees of freedom of the specimen assumed as a discrete Lumped-mass system. This hybrid feature of the Pseudo-dynamic method becomes an advantage; however, at the same time it could generate certain types of errors that would deteriorate the accuracy of the method. Generally speaking, these mentioned errors are classified into two groups: Intrinsic Errors and Experimental Errors.

It is important to remember that the analytical part in the procedure of the Pseudo-dynamic technique brings inevitable assumptions and simplifications, which would mean an apparent approaching of the true response. Because the errors generated by these assumptions are of inherent origin, one can classify this type of error as intrinsic errors [5], [12]. The major sources of intrinsic error are the following: (1) The discrete mass-spring idealization of the specimen, which strictly has a continuous mass along of its dimension. (2) The mathematical solution of the equation of motion by means of a discretized numerical integration with respect to time domain. Stability and accuracy will depend on the choice of time step Δt and the integration method used, as it was seen in section 3.1. (3) The selection of a velocity-dependent equivalent viscous damping, considering that the energy dissipation mechanisms manifest in several ways and could occur at the same time (Coulomb damping, hysteretic damping, etc.) [13].

Despite the previously specified limitations, intrinsic errors are not commonly the main source of error in a Pseudo-dynamic test. In contrast, the experimental errors could cause considerable inaccuracies in the structural response. For these reasons, these errors have had an important scientific relevance for many researchers throughout the development of the Pseudo-dynamic Test technique [14]. The computed displacement will depend on the response previously measured experimentally by the feedback control system both in load and in displacement. Then, these previous steps conditions could accumulate errors that would be negatively very sensitive to the subsequent estimated responses. The displacement cumulative error could be reduced if the computed displacements are used instead of the displacements recorded for the estimation of the next displacement response [9]. However, the loading cumulative error could deteriorate the displacement response because, as mentioned in the previous sections, the restoring force is measured directly during the test and it could be with an undershoot or overshoot condition. Nakashima et. al. [15] proposed a characterization of error force ($\Delta\{R\}$) by considering it as a proportional dependence of the displacement error ($e_j=\{X\}^{t+\Delta t}-\{X_j\}$) using the instantaneous stiffness ($\{K\}^{t+\Delta t}$), as described in the Eq. (8).

$$\Delta\{R\} = \{K\}^{t+\Delta t}.(\{X\}^{t+\Delta t} - \{X_j\}) \tag{8}$$

The Eq. (9) shows the Eq. (2) with an extra participation of the loading experimental error. The overshoot condition would mean a certain non-desired loading extra measurement that it will be correct by the value of $\Delta\{R\}$. A similar situation applies for the undershoot condition. In this condition, there is an incorrect loading measurement, which would be below the true value. Therefore, it would add the value of $\Delta\{R\}$ to the restoring force in order to approach the true loading response of the specimen.

$$[M].\{\ddot{X}\}^{t+\Delta t} + [C].\{\dot{X}\}^{t+\Delta t} + \{R\}^{t+\Delta t} = \{f\}^{t+\Delta t} + \Delta\{R\} \quad (9)$$

The displacement error must be less than the tolerance e, because to the value of X_j in the Eq. 9 is supposed as the displacement sensed from LVDT transducer when the displacement control converges to the target displacement under the conditions of the Control Criteria discussed above.

4. Experimental Study

4.1 Description of Specimens

The specimens for the Pseudodynamic tests were built by using a ASTM LAC A500 steel section of 100x100x6 mm. The lower part of the steel column was welded to a base plate which in turn is fixed to a concrete reaction block by means of four anchor bolts of 3/4 inch of diameter. Likewise, the top of the steel colum was attached to a 5/8 inch thick steel plate in order to ensure the assembly of the head of the eletro-hydraulic actuator, as seen in Fig. 3.

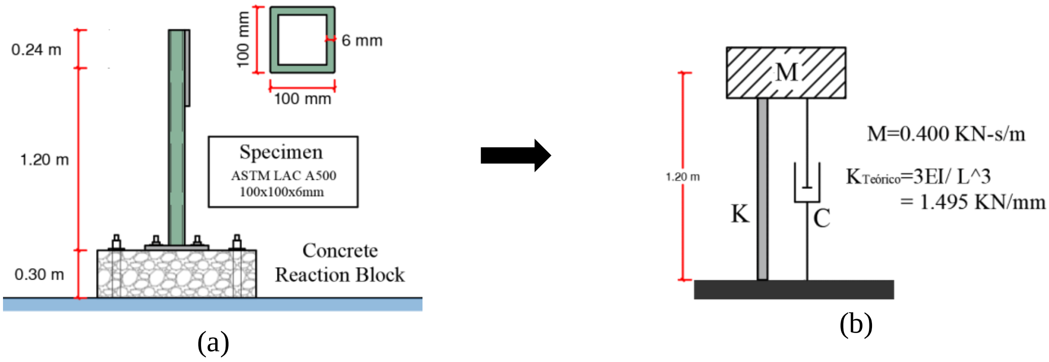


Fig. 3 – (a) The Specimen for Pseudo-dynamic Test. (b) Idealization of Specimen.

4.2 Free Vibration Test

A set of free vibration tests (VL01-VL08) was performed in order to determine the dynamic properties of the specimens like the fundamental period and the equivalent viscous damping. In the free vibration tests, acceleration measuring in the corresponding degree of freedom of the specimen was recorded, as shown in Fig. 4. The experimental dynamic properties were estimated by adjusting the dynamic movement to a sub-damping logarithmic decrement mechanism. In this way, the average equivalent viscous damping and the average fundamental period is summarized in Table 1.

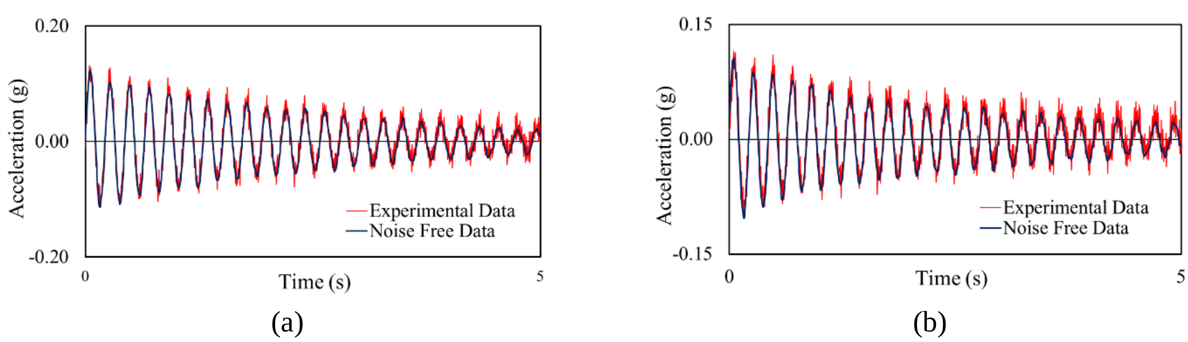


Fig. 4 – Acceleration Response of Free Vibration Test. (a) VL03. (b) VL07.

Based on the results of the free vibration tests, one can estimate the interval in where the Explicit Newmark Method is stable ($\Delta t <= 0.0680$ s); and also, the damping coefficient of the specimen (C = 0.412 KN.s / m). However, an interval that satisfice the stability condition does not ensure an adequate response approaching in the Pseudo-dynamic Test. In addition, for random excitations like seismic movement, the value of Δt can have an important and negative influence on the displacement response [4]. For these reasons, Mahin et. al. [5] recommend using an interval no greater than 0.05.T = 0.0107 s. The interval chosen for the two Pseudo-dynamic tests was Δt = 0.01 s, which therefore complies the recommendations of the reference.

Table 1 – Free Vibration Test

Free Vibration Test – PSD1	**Period (s)**	**Viscous Damping ratio (%)**	**Free Vibration Test – PSD2**	**Period (s)**	**Viscous Damping ratio (%)**
VL-01	0.2139	1.393	VL-05	0.2150	1.555
VL-02	0.2146	1.531	VL-06	0.2127	1.544
VL-03	0.2135	1.484	VL-07	0.2140	1.420
VL-04	0.2132	1.511	VL-08	0.2131	1.465
Average Value	**T=0.2138 s**	**b=1.480 %**	Average Value	**T=0.2137 s**	**b=1.496%**

4.2 Pseudo-dynamic Test

Two Pseudo-dynamic tests (PSD1, PSD2) are performed for two steel tubular columns specimens under two and fifteen real second of excitations, which correspond to Pseudo-dynamic times of 17 min and 136 min, respectively. The tests PSD1, PSD2 were carried out with an integration time interval Δt of 0.01 s by involving 200 and 1500 time steps. The first excitation corresponds to a sinusoidal movement with a maximum acceleration of 0.5g and a period of 0.14 seconds, as seen in Fig. 5 (a). Likewise, the second test was performed by using an important part of 15 seconds of the Lima 1974 earthquake acceleration record excitation (see Fig. 5 (b)) with an amplification of 2g. Moreover, a summary of the main characteristics of the Pseudo-dynamic Tests are shown in the Table 2.

The specimens could be idealizated as a Lumped-Mass 1DOF system as shown above in Fig. 3. On the other hand, the Fig. 6 describes the set-up of the Pseudo-dynamic tests. The CH-00, CH-01, CH-02 Chanels, which correspond to load cell, analog displacement transducer and actuator stroke measurement, respectively, were monitored throughout the tests by means of the feed-back control.

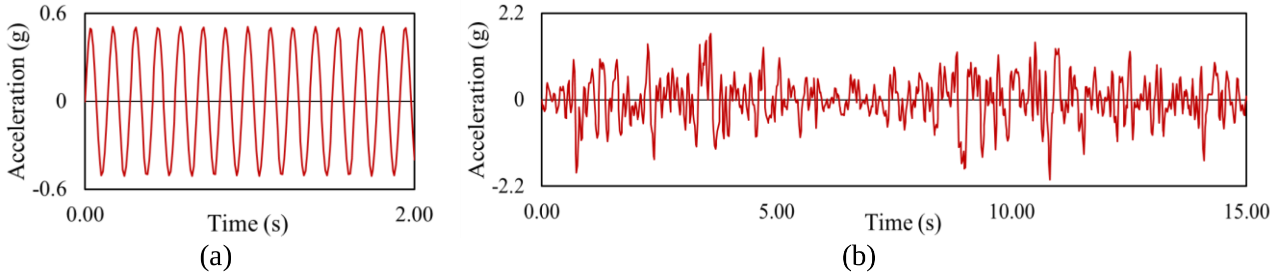


Fig. 5 – Input Acceleration Excitation for Pseudo-dynamic Tests. (a) PSD1. (b) PSD2.

Table 2 – Characteristics of Pseudo-dynamic Tests

Pseudo-dynamic Test	**Excitation PGA**	**Real Duration (TD)**	**Pseudo-dynamic Duration (PsT)**	**Duration Ratio (TD/PsT)**	**Maximum Displacement**	**Maximum Restoring Force**
PSD1	0.5 g	2 s	17 min	1/510	4.621 mm	6.097 KN
PSD2	2.0 g	15 s	136 min	1/544	2.227 mm	21.868 KN

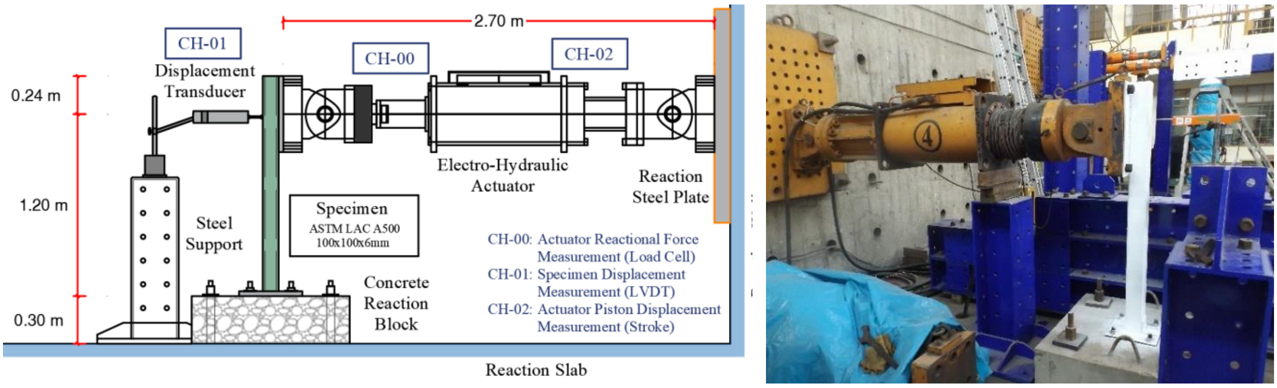


Fig. 6 – Set-up for the Pseudo-dynamic Test.

5. Verification of Pseudo-dynamic Testing Results

A comparison between the experimental response (both in displacement and in restoring force) obtained from the Pseudo-dynamic tests with the analytical response in Stera3D v.10.3 software [16] was performed in order to assess the reliability of the algorithm proposed in this research. In the analytical simulation, a lineal elastic behavior in the tests (PSD1, PSD2) was considered. Furthermore, a dissipated energy was observed at the capacity curve of specimens that could derivate from the Coulomb damping of the apparatus involved in the Pseudo-dynamic Test [5]. These energy dissipations were estimated as equivalent viscous damping ratios of 6.14% for the PSD1 Test and of 5.30% for the PSD2 Test. A system conformed by the steel column specimen, the steel connections, the welding and the electro-hydraulic actuator was considered for the performing of the analytical simulations. Thus, the equivalent viscous damping ratio was considered as a representative value of damping of the entire system and, moreover, it was inputted into the analytical simulation corresponding to PSD1 or PSD2. The analytical and experimental results of PSD1 and PSD2 tests are illustrated in the Fig. 7 and Fig. 8, respectively.

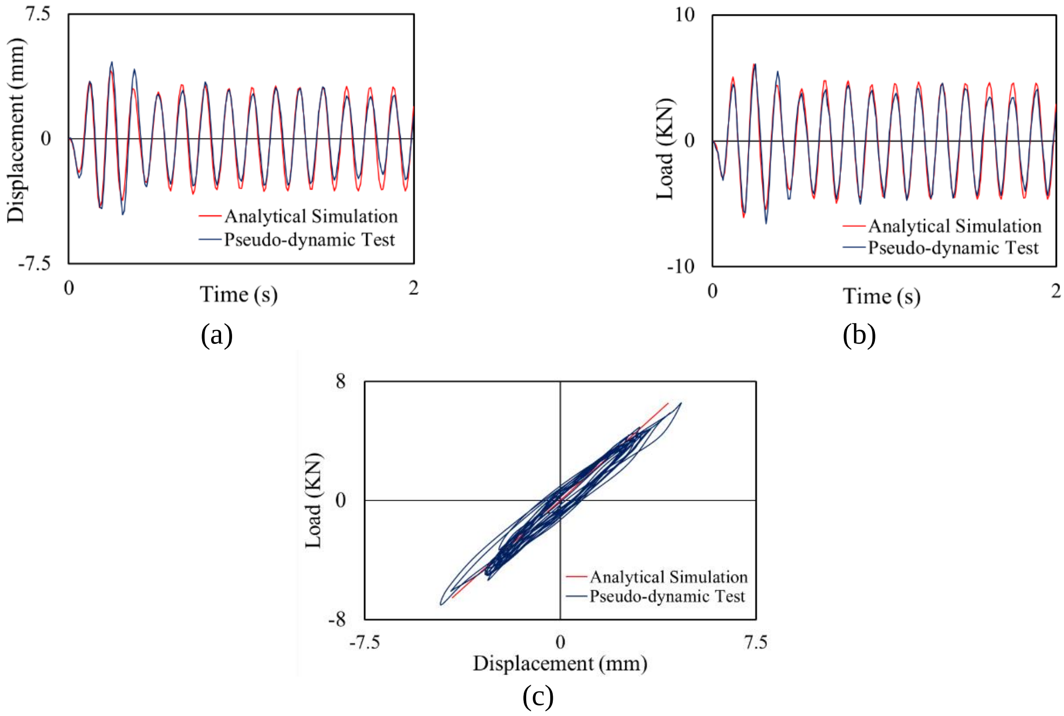
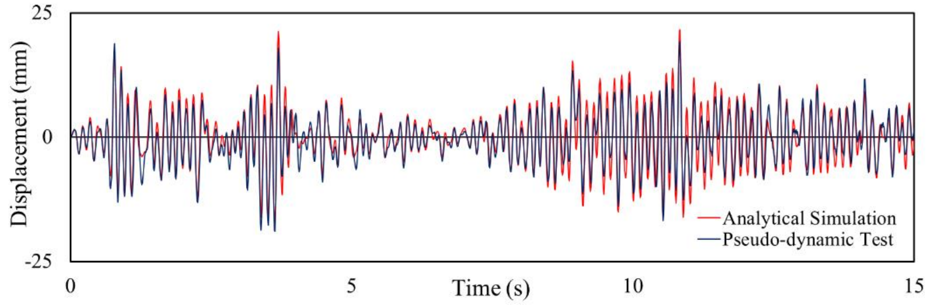
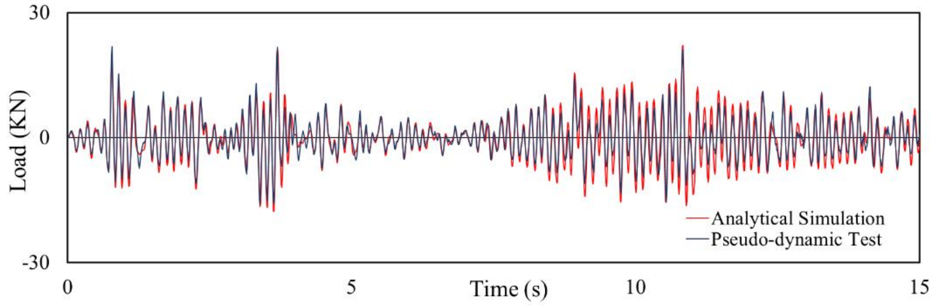


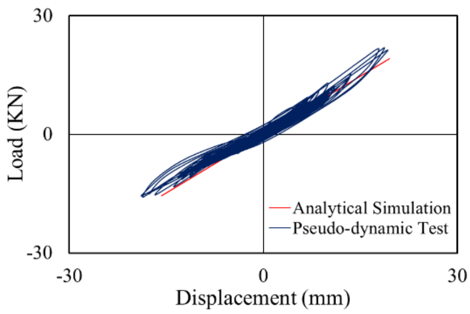
Fig. 7 – The Pseudo-dynamic Testing Results - PSD1. (a) Displacement Response. (b) Restoring Force Response. (c) Capacity Curve.



(a)



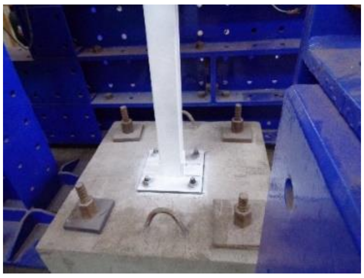
(b)



(c)

Fig. 8 – The Pseudo-dynamic Testing Results – PSD2. (a) Displacement Response. (b) Restoring Force Response. (c) Capacity Curve.

The Fig. 9 show the status of the specimens once the PSD1 and PSD2 tests have been completed. Furthermore, it can be seen that there were not visible damages that mean the non-lineal behavior of the specimens. Therefore, as mentioned above, a lineal response was considered for both tests.



(a)

(b)

Fig. 9 – The steel column specimen after the test. (a) PSD1. (b) PSD2.

6. Conclusions

In this report, the experimental and analytical procedure of the Pseudo-dynamic method has been examined and developed. Moreover, the reliability of the CISMID Pseudo-dynamic Testing program was verified by means of analytical time-history simulation in Stera3D software for a single degree of freedom specimen. The capabilities of Pseudo-dynamic technique are evident, however, also there are certain difficulties that must be recognized because they could deteriorate the true structural response. Therefore, the advantages and disadvantages of the Pseudo-dynamic testing program proposed in this research are examined with the following conclusions:

1. The Conventional Pseudo-dynamic Test is a hybrid experimental technique that use advantageously the features of the experimental test with the mathematical solving of the structural response of specimen under a quasi-static load. This quasi-static load is slowly imposed on the specimen with a rapidity of approximately 5 seconds per time step. In other words, 1 excitation real-time second with an integration time interval of 0.01 seconds would mean approximately 500 real-time seconds for the Pseudo-dynamic testing response, as previously shown in Table 2. Due to this sluggish motion and considering that the true response is given by dynamic excitation, inaccuracies by strain-rate effects could not be neglected when the specimen is involved in non-lineal status and moreover, this effects could become very important if a concrete specimen is tested because its cracking failure mechanism presents during a dynamic motion [4].
2. The inherent damping of a structural system could manifest in different ways, such as hysteretic, Coulomb and viscous damping. Generally, in the Structural Dynamic, the damping capacity is simplified assuming a viscous equivalent damping to the whole structure. Therefore, the equivalent viscous damping ratio of approximately 1.5% estimated by means of the free vibration tests (Table 1) could correctly approach to the true value of the damping of the specimen. However, the damping capacity is not a single value, it depends on the amplitude of the drifts and the level of excitation involved the motion of the structure. Then, it is necessary to perform a better estimation of the damping capacity if more realistic values are required in the response of the structure. On the other hand, due to that this research specifically aims the successful performance of the on-line control program, the authors consider that the equivalent viscous damping ratio calculated of the free vibration tests could be used correctly in these tests.
3. According to the displacement and restoring force time histories of the Fig. 7 and Fig. 8, the reliability of the conventional Pseudo-dynamic technique has been verified by means of the correct correlation of the experimental response and the analytical results performed in Stera3D program. However, this research is limited to demonstrate the proper functioning of the On-Line program for a single degree of freedom system. For systems that involve two or more degree of freedom, the stability conditions are more strict if a conditional explicit methods is used; furthermore, experimental feedback errors could accumulate rapidly with the higher modes of vibration of the MDOF system due to resonance-like effects of the systematic errors, and undesired distortions in the Pseudo-dynamic test could be introduced on the response [9].
4. In the displacement time histories of the Fig. 7 (a) and Fig. 8 (a), considerable non-lineal period elongations have not been observed. In addition, there was no observable damage in the specimens involved non-lineal range once the tests have been completed, as previously shown in Fig. 9. For these reasons, lineal behavior response was considered for the analytical simulations of the PSD1 and PSD2 tests.
5. The capacity curves of the Fig. 7 (c) and Fig. 8 (c) show a dissipation energy corresponding to area enclosed under the hysteresis loops. As mentioned above, this energy dissipation is caused by the Coulomb damping of the apparatus involved in the specimen-actuator system [5]. Moreover, this energy was calculated as an equivalent viscous damping ratio of approximately 6.14% for PSD1 Test and 5.30% for PSD2 Test. The analytical simulations consider these viscous damping ratios in order to represent as real as possible the structural behavior of the system.

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8. References

[1] Takanashi K, Nakashima M (1987): Japanese Activities on On-Line Testing. *Journal of Structural Engineering ASCE*, **113** (7), 1014-1032.

[2] Hakuno M, Shidawara M, Hara T (1969): Dynamic destructive test of a Cantilever beam, controlled by an analogic-computer. Trans. Japan Society of Civ. Engrs., N°171, Tokyo, Japan.

[3] Takanashi K, Udagawa K, Seki M, Okada T, Tanaka H (1975): Nonlinear Earthquake Response Analysis of Structures by a Computer-Actuator On-Line System. Bulletin of Earthquake Resistant Structure Research Center, Nº 8, Institute of Industrial Science, University of Tokyo, Tokyo, Japan.

[4] Shing PS, Mahin S (1984): Pseudodynamic Test Method for Seismic Performance Evaluation: Theory and Implementation. Report UCB/EERC-1984/01, Earthquake Engineering Research Center, Berkeley, USA.

[5] Mahin S, Shing PS (1985): Pseudodynamic Method for Seismic Testing. *Journal of Structural Engineering, ASCE*, **111** (7), 1482-1503.

[6] Donea J, Magnotte G, Negro P, EERI, Pegon P, Pinto A, Verzeletti G (1996): Pseudodynamic Capabilities of the ELSA Laboratory for Earthquake Testing of Large Structures. Earthquake Spectra, **12°**(1), 163-180.

[7] Chunga C. (2001): Desarrollo de software para el control de actuadores En-línea en ensayos de estructuras a escala natural. Undergraduate Thesis. Faculty of Civil Engineering of National University of Engineering, Lima, Peru.

[8] Bathe KJ (2014). Finite Element Procedures. 2nd edition.

[9] Shing PS, Mahin S (1987): Cumulative Experimental Errors in Pseudodynamic Tests. Earthquake Engineering and Structural Dynamics, **15°**, 409-424.

[10] Zavala C. (1994): A Study on Substructuring Hybrid Simulation for Flexible Steel Framed Structures. Doctoral Thesis. Graduated School of Engineering of The University of Tokyo, Tokyo, Japan.

[11] Ohi K, Takanashi K (1988): An Improvement of On-line Computer Test Control Method. *9th World Conference on Earthquake Engineering*, Tokyo-Kyoto, Japan.

[12] Nakashima M, Kato H (1988): Part 3, Experimental Error Growth in Pseudo Dynamic Testing. *Journal of Structural and Construction Engineering* (Transactions of AIJ), N° 386.

[13] Shibata A (2010): *Dynamic Analysis of Earthquake Resistant Structures*. Tohoku University Press, 2nd edition.

[14] Shing PS, Mahin S (1985): Experimental Error Effects in Pseudodynamic Testing. *Journal of Engineering Mechanics*, **116** (4), 24541.

[15] Nakashima M, Kato H (1989): Part 4, Control of Experimental Error Growth in Pseudo Dynamic Testing. *Journal of Structural and Construction Engineering* (Transactions of AIJ), N° 401.

[16] Saito, T (2015): Stera 3D. http://www.rc.ace.tut.ac.jp/saito/software-e.html