

Dynamic Evaluation of Existing Reinforced Concrete Buildings Using the Pushover (Nonlinear Static) Method

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Abstract:

The pushover (nonlinear static) analysis has become a widely adopted tool for the seismic evaluation of both existing and new reinforced concrete (RC) structures. Public RC buildings in Libya, many of which were constructed over the past two to three decades, may now be seismically deficient because design code requirements have been progressively updated. In this study, the pushover method is applied to a simple framed RC structure and to an existing RC building in Libya, with the aim of tracking hinge deformation, identifying failure modes, and locating the global performance point. The analysis is carried out using the well-known SAP2000 software package. Modelling the complex nonlinear behaviour of RC buildings analytically remains a challenging task; consequently, engineers have historically relied on empirical formulas derived from extensive experimental programmes. With recent advances in structural analysis software and computational capacity, nonlinear analysis, including three-dimensional modelling, has become an indispensable tool for structural assessment (Maulana et al., 2025). The pushover method offers a relatively simple means of evaluating the present state of existing buildings and of assessing whether newly designed but not-yet-constructed buildings can resist extreme earthquake and wind loads. Where the results indicate that a building cannot withstand such loads without unacceptable damage, the pushover analysis provides the information needed to decide on appropriate remedial measures (Guetala et al., 2025).

Keywords: Pushover analysis; Nonlinear static analysis; Reinforced concrete buildings; Seismic evaluation; SAP2000; Performance point; Plastic hinges; Structural assessment.

المخلص

أصبح التحليل بالدفع التدريجي (التحليل اللاخطي الساكن) أداة واسعة الاعتماد للتقييم الزلزالي للمنشآت الخرسانية المسلحة القائمة والجديدة على حد سواء. وقد تكون المباني الخرسانية المسلحة العامة في ليبيا، التي شُيِّد الكثير منها خلال العقدين أو الثلاثة عقود الماضية، معرضة الآن لقصور زلزالي بسبب التحديث التدريجي لمتطلبات أكواد التصميم. في هذه الدراسة، تُطبَّق طريقة الدفع التدريجي على منشأ خرساني مسلح بسيط مؤطر وعلى مبنى خرساني مسلح قائم في ليبيا، بهدف تتبع تشوه المفاصل، وتحديد أنماط الانهيار، وتحديد نقطة الأداء العامة. وقد أُجري التحليل باستخدام حزمة البرامج المعروفة SAP2000. ولا يزال النمذجة التحليلية للسلوك اللاخطي للمعدن للمباني الخرسانية المسلحة مهمة صعبة؛ ونتيجة لذلك، اعتمد المهندسون تاريخياً على صيغ تجريبية مستمدة من برامج تجريبية موسعة. ومع التقدم الحديث في برمجيات التحليل الإنشائي والقدرة الحاسوبية، أصبح التحليل اللاخطي، بما في ذلك النمذجة ثلاثية الأبعاد، أداة لا غنى عنها لتقييم المنشآت

(Maulana et al., 2025). وتقدم طريقة الدفع التدريجي وسيلة بسيطة نسبياً لتقييم الحالة الراهنة للمباني القائمة، ولتقييم ما إذا كانت المباني المصممة حديثاً ولكن غير المشيئة بعد قدرة على مقاومة أحمال الزلازل والرياح القصوى. وعندما تشير النتائج إلى أن المبنى غير قادر على تحمل هذه الأحمال دون ضرر غير مقبول، فإن تحليل الدفع التدريجي يوفر المعلومات اللازمة لاتخاذ القرار بشأن التدابير العلاجية المناسبة..

الكلمات المفتاحية: تحليل الدفع التدريجي؛ التحليل اللاخطي الساكن؛ المباني الخرسانية المسلحة؛ التقييم الزلزالي؛ SAP2000؛ نقطة الأداء؛ المفاصل البلاستيكية؛ تقييم المنشآت.

Introduction

The nonlinear structural analysis approach has become an essential tool for the assessment of engineering structures subjected to extreme loading, particularly earthquakes. The advent of advanced structural analysis software has made nonlinear analysis feasible for practising engineers, and the pushover (nonlinear static) method can be regarded as a simplified procedure that treats nonlinear structural behaviour in an accessible form (Maulana et al., 2025). This approach enables engineers to evaluate the present state of existing and new buildings with respect to their capacity to resist extreme earthquake and wind loading, and to decide what action to take when the results show that a building cannot withstand these loads without unacceptable damage. For existing buildings, pushover analysis can also inform future rehabilitation plans (Guettala et al., 2025).

The present work is concerned with presenting the pushover analysis method to practising engineers in sufficient detail for future use, describing the advanced software packages that implement this method, such as SAP2000, and demonstrating its application to reinforced concrete buildings.

1.1 Subject Background

The planning, design, and construction of high-rise buildings under dynamic loads have undergone significant development worldwide. Engineers study the effects of earthquakes and wind on buildings and are increasingly concerned with the rehabilitation of older structures. Maintenance requires a comprehensive assessment of future performance, and dynamic analysis can evaluate a building's strength and integrity so that maintenance procedures can be planned to ensure the continued ability of the structure and its components to resist dynamic loads (Soliman et al., 2025). Some older buildings may never have been designed or checked for such loads. Nonlinear static and nonlinear dynamic analyses are not easy tasks, particularly for complex structural buildings, old or new (Maulana et al., 2025). Past practice relied on linear static or quasi-dynamic analysis to make engineering work practical, and although such approaches are approximate, they often fulfilled most needs. With modern fast computers and advanced software packages, nonlinear analysis has become more accessible, and some methods are now simpler to perform. One such method is the pushover (static-nonlinear) analysis, which is recognised as an accepted evaluation method for existing structures under dynamic loading (Al-Arab et al., 2025). This method has become popular because it can be implemented with relative ease and used to evaluate the strength state and performance of old and new buildings. Using well-known commercial software such as SAP2000, the analysis can be performed efficiently (Bassurucu et al., 2025); other packages such as ETABS, STAAD.Pro, and Robot are also available. Nonlinear static analysis, or pushover analysis, has been developed over the past two decades and has become a preferred procedure for design and seismic performance evaluation because it is relatively simple and considers post-elastic behaviour. However, the procedure involves certain approximations and simplifications, and some variation in seismic demand prediction is always expected (Al-Arab et al., 2025). Pushover analysis has been shown to capture essential structural response characteristics under seismic action. It is an approximate method in which the structure is subjected to monotonically increasing lateral forces until a target displacement is reached. The method is based on a series of sequential elastic analyses superimposed to approximate a force-displacement curve for the whole structure and can be conducted as either a force-controlled or a displacement-controlled procedure (Kuria & Kegyes-Brassai, 2024).

1.2 Objectives of the Present Research Work

The objectives of the present research work are:

1. To present the pushover (nonlinear static) analysis as a practical method that provides information on response characteristics that cannot be obtained from elastic static or dynamic analysis alone (Guettala et al., 2025).
2. To describe the method in sufficient detail for practising engineers to use it in future work (Maulana et al., 2025).
3. To introduce advanced software packages that implement this method for nonlinear structural behaviour, such as SAP2000 (Bassurucu et al., 2025).

4. To apply the method to a simple framed RC building and to an existing RC building in Libya using SAP2000.
 5. To discuss the advantages and limitations of the procedure (Soliman et al., 2025).
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2. The Pushover Method of Analysis

The pushover (static nonlinear) method is increasingly used to predict seismic force and deformation demands for the performance evaluation of existing and new structures. When applied thoughtfully and with good engineering judgement, it provides useful information that cannot be obtained from elastic static or dynamic analysis. Pushover analysis allows engineers to follow procedures such as FEMA-356 and ATC-40 (Ghosh et al., 2025). The method uses simplified nonlinear techniques to estimate seismic structural deformations. It is an incremental static analysis used to determine the force–displacement relationship, or capacity curve, for a structure or structural element. The analysis involves applying horizontal loads in a prescribed pattern to the structure incrementally, pushing the structure, and plotting the total applied shear force and associated lateral displacement at each increment until the structure reaches a collapse condition (Maulana et al., 2025).

2.1 Pushover Analysis Procedure

The pushover analysis procedure represents the structure in a two- or three-dimensional analytical model that accounts for all important linear and nonlinear response characteristics, applies gravity loads first, and then applies lateral loads in predetermined patterns that approximately represent the relative inertia forces generated at locations of substantial mass. The structure is pushed under these load patterns to specific target displacement levels. Internal forces and deformations computed at the target displacement levels are estimates of strength and deformation demands, which must be compared with available capacities (Al-Arab et al., 2025). Gravity loads are applied first, and lateral loads are then applied incrementally. In simple cases, the analysis can be performed as a series of elastic analyses in which points where the bending strength has been reached are treated as hinges under additional lateral loads. Bilinear or multilinear load–deformation diagrams must be incorporated if strain hardening or softening is important (Guettala et al., 2025). The analysis continues beyond the target displacement, producing a base shear versus roof displacement response. In most cases, displacement control is necessary because the target displacement may be associated with very small positive or even negative lateral stiffness due to mechanism development and P-delta effects. At the target displacement level, member forces and deformations, for example plastic hinge rotations, are compared with available capacities for performance evaluation (Kuria & Kegyes-Brassai, 2024).

2.2 Background to Pushover Analysis

The static pushover analysis has no rigorous theoretical foundation. It is based on the assumption that the response of the structure can be related to the response of an equivalent single-degree-of-freedom (SDOF) system. This implies that the response is controlled by a single mode and that the shape of this mode remains constant throughout the time-history response. Both assumptions are incorrect, but pilot studies by several investigators have indicated that they lead to reasonably good predictions of the maximum seismic response of multi-degree-of-freedom (MDOF) structures, provided that the response is dominated by a single mode (Soliman et al., 2025). The formulation of the equivalent SDOF system is not unique, but the common basic assumption is that the deflected shape of the MDOF system can be represented by a shape vector that characterises the elastic and inelastic response of the structure.

In the capacity spectrum method, the properties of the equivalent SDOF system, the capacity spectrum, are determined, and the target displacement is estimated by intersecting this capacity spectrum with a modified demand spectrum that accounts for inelastic response through period shift and increased viscous damping (Ghosh et al., 2025). The capacity spectrum properties, spectral acceleration S_a and spectral displacement S_d , are obtained from the base shear–roof displacement diagram through transformations involving the modal mass coefficient and participation factor for the first natural mode. Discrete values for S_a and S_d are determined at points where the capacity curve shows evident kinks, with the shape vector updated to correspond to the first mode shape at the displacement level (Al-Arab et al., 2025).

To identify nominal global strength and displacement quantities, the multilinear capacity curve must be represented by a bilinear relationship that defines a yield strength, an effective elastic stiffness, and a hardening or softening stiffness for the structure. Some judgement may be needed to define these properties. The simplified bilinear base shear–roof displacement response curve is needed to define the properties of the equivalent SDOF system (Soliman et al., 2025). The yield value of the base shear and the corresponding roof displacement are used together with the transformation equations to compute the force–displacement relationship for the equivalent SDOF system. The initial period of the equivalent SDOF system can then be computed, and the strain-hardening

ratio of the MDOF structure defines the strain-hardening ratio of the equivalent SDOF system (Guettala et al., 2025).

The basic properties of the equivalent SDOF system are now known. The roof displacement of the structure is related to the equivalent SDOF displacement, so the target displacement can be found if the displacement demand of the equivalent SDOF system can be estimated for the design earthquake. The utilisation of inelastic spectral demand information requires estimation of the ratio of elastic strength demand to yield strength of the equivalent SDOF system, usually referred to as the R-factor. Since inelastic spectra are usually obtained for unit-mass systems, it is convenient to divide the governing equation by the equivalent mass to obtain the differential equation of the unit-mass equivalent SDOF system. If an elastic design spectrum is given, the elastic strength demand of the unit-mass equivalent SDOF system can be computed, and the strength reduction factor R can then be obtained (Soliman et al., 2025).

Both the R-factor and the target displacement depend on the choice of the shape vector. Most investigators who have utilised pushover analysis in pilot studies have recommended using the normalised displacement profile at the target displacement level as the shape vector. Since this displacement is not known a priori, an iteration process must be performed if this shape vector is selected. The use of the equivalent period and the aforementioned shape vector for estimating the properties of the equivalent SDOF system and the target displacement requires elaborate computations and time-consuming iterations. Recognising all the assumptions and approximations inherent in the pushover procedure, there is no strong justification for being rigorous in the computations leading to the target displacement estimate, and accuracy can often be sacrificed for simplicity (Al-Arab et al., 2025).

2.3 Limitations of Pushover Analysis

Pushover analysis has advantages over elastic analysis procedures, but the accuracy of its predictions and the limitations of current procedures must be identified. Important aspects that affect the accuracy of pushover results include the estimate of target displacement, the selection of lateral load patterns, and the identification of failure mechanisms due to higher modes of vibration (Soliman et al., 2025). The displacement of concern is the global displacement expected in a design earthquake, and the displacement at the mass centre of the roof is generally considered the target displacement. Accurate estimation of target displacement for a specific performance objective affects the accuracy of seismic demand predictions. However, pushover analysis generally uses an invariant lateral load pattern, assuming that the distribution of inertia forces is constant during the earthquake and that the deformed configuration of the structure under the invariant lateral load pattern is similar to that experienced in the design earthquake. Because the capacity curve is very sensitive to the choice of lateral load distribution, the selection of the lateral load pattern is more critical than the accurate estimation of target displacement (Guettala et al., 2025).

The lateral load patterns used in pushover analysis are proportional to the product of storey mass and displacement associated with a shape vector at the storey under consideration. Commonly used patterns are uniform, elastic first-mode, code distributions, and a single concentrated horizontal force at the top of the structure. A multimodal load pattern derived from the square root of the sum of squares of storey shears is also used to consider at least elastic higher-mode effects for long-period structures. These loading patterns usually favour certain deformation modes triggered by the load pattern while missing others initiated and propagated by ground motion and the inelastic dynamic response characteristics of the structure. Moreover, invariant lateral load patterns cannot predict potential failure modes due to middle- or upper-storey mechanisms caused by higher-mode effects. Invariant load patterns can provide adequate predictions if the structural response is not severely affected by higher modes and if the structure has only a single load-yielding mechanism that can be captured by an invariant load pattern (Soliman et al., 2025).

FEMA-356 recommends using at least two fixed load patterns that form upper and lower bounds for inertia force distributions to predict likely variations in overall structural behaviour and local demands. The first pattern should be a uniform load distribution, and the other should be a code profile or a multimodal load pattern. The lateral load pattern proposed by code provisions is permitted if more than 75% of the total mass participates in the fundamental loading. Invariant load patterns cannot account for the redistribution of inertia forces due to progressive yielding and the resulting changes in the dynamic properties of the structure. Fixed load patterns also have limited capability to predict higher-mode effects in the post-elastic range. These limitations have led many researchers to propose adaptive load patterns that consider changes in inertia forces with the level of inelasticity. The underlying approach is to redistribute the lateral load shape with the extent of inelastic deformations. Although some improved predictions have been obtained from adaptive load patterns, they make pushover analysis computationally demanding and conceptually complicated. The scale of improvement remains a subject of discussion, and simple invariant load patterns are widely preferred at the expense of accuracy. Lateral load is

applied statically, but static loading cannot represent inelastic dynamic response with a high degree of accuracy (Guettala et al., 2025; Soliman et al., 2025).

2.4 Elastic and Inelastic Methods of Analysis

Methods used for the seismic evaluation of engineering structures can be either elastic or inelastic.

2.4.1 Elastic Methods of Analysis

Elastic analysis methods include the static lateral force approach and the dynamic load approach based on code requirements. These methods assume that structures respond elastically to earthquakes. In the static lateral force approach, a static analysis is performed by subjecting the structure to lateral forces obtained by scaling down the smoothed soil-dependent elastic response spectrum by a structural-system-dependent force reduction factor R . This approach assumes that the actual strength of the structure is higher than the design strength and that the structure can dissipate energy through yielding. In the dynamic approach, force demands on various components are determined by elastic dynamic analysis, either response spectrum analysis or elastic time-history analysis. A sufficient number of modes must be considered to achieve at least 90% mass participation in response spectrum analysis. Higher-mode effects are automatically included in time-history analysis (Ghosh et al., 2025).

In the demand/capacity ratio (DCR) procedure, force actions are compared with corresponding capacities as demand/capacity ratios. Demands for DCR calculations must include gravity effects. While static lateral force and dynamic procedures reduce the full earthquake demand by an R -factor, the DCR approach takes the full earthquake demand without reduction and adds it to gravity demands. DCR values approaching or exceeding 1.0 may indicate potential deficiencies (Maulana et al., 2025).

Force-based procedures are well known to the engineering profession and are easy to apply, but they have certain drawbacks. Structural components are evaluated for serviceability in the elastic range of strength and deformation, and post-elastic behaviour cannot be identified by elastic analysis. Post-elastic behaviour should be considered because almost all structures are expected to deform inelastically during a strong earthquake. The seismic force reduction factor R accounts for inelastic behaviour indirectly by reducing elastic forces to inelastic values. The force reduction factor is assigned considering only the type of lateral system in most codes, but it has been shown to be a function of the period and ductility ratio of the structure as well. Elastic methods can predict the elastic capacity of a structure and indicate where the first yielding will occur, but they do not predict failure mechanisms or account for the redistribution of forces as yielding progresses. Real deficiencies present in the structure could be missed. Moreover, force-based methods primarily provide life safety but cannot provide damage limitation and easy repair (Soliman et al., 2025).

2.4.2 Inelastic Methods of Analysis

Strong earthquakes cause significant inelastic deformation in engineering structures. Accordingly, the dynamic characteristics of the structure change with time, and investigating structural performance requires inelastic analytical procedures that account for these aspects. The actual behaviour of structures can be better understood by using inelastic analytical procedures that identify failure modes and the potential for progressive collapse. Inelastic analysis procedures include inelastic time-history analysis and inelastic static analysis, also known as pushover analysis. Inelastic time-history analysis is the most accurate method for predicting force and deformation demands at various structural components. However, its use is limited because dynamic response is very sensitive to modelling and ground-motion characteristics. It requires proper modelling of cyclic load–deformation characteristics considering the deterioration properties of all important components, and it also requires a set of representative ground-motion records that accounts for uncertainties and differences in severity, frequency, and duration characteristics. The time required for input preparation and interpretation of the large output, computation time, makes inelastic time-history analysis impractical for routine seismic performance evaluation (Maulana et al., 2025).

Inelastic static analysis, or pushover analysis, has been the preferred method for seismic performance evaluation because of its simplicity. It is a static analysis that directly incorporates nonlinear material characteristics. Inelastic static analysis procedures include the capacity spectrum method, the displacement coefficient method, and the secant method (Ghosh et al., 2025).

2.5 Seismic Evaluation by ATC-40

Seismic evaluation can be performed using the step-by-step procedure prescribed in ATC-40 for developing the capacity curve.

2.5.1 Determination of Capacity by Step-by-Step Procedure

The most convenient way to plot the force–displacement curve is by tracking the base shear and roof displacement. The capacity curve is generally constructed to represent the first-mode response of the structure, based on the assumption that the fundamental mode of vibration is the predominant response. This is generally valid for buildings with fundamental periods of vibration up to about one second. For more flexible buildings with fundamental periods greater than one second, higher-mode effects should be considered (Ghosh et al., 2025). A computer model of the structure is created following ATC-40 modelling rules. Each element is classified as either primary or secondary, and lateral storey forces are applied in proportion to the product of mass and fundamental mode shape. The analysis should also include gravity loads. The term pushover implies pushing the structure horizontally with a prescribed loading pattern incrementally until the structure reaches a limit state. Several levels of sophistication may be used: applying a single concentrated horizontal force at the top, applying lateral forces to each storey in proportion to the standard code procedure, or applying lateral forces in proportion to the product of storey masses and the first-mode shape (Al-Arab et al., 2025).

The capacity curve is generally constructed to represent the first-mode response. Lateral forces are applied until first yielding. For each increment beyond yielding, the forces are adjusted to be consistent with the changing deflected shape, or higher-mode effects are included in determining yielding in individual elements while plotting the capacity curve in terms of first-mode lateral forces and displacements. Higher-mode effects may be determined by performing higher-mode pushover analysis, in which loads are progressively applied in proportion to a mode shape other than the fundamental mode to determine its inelastic behaviour. For higher modes, the structure is both pushed and pulled concurrently to maintain the mode shape. The lateral force level is adjusted so that some elements are stressed to within 10% of their member strength. The base shear and roof displacement are recorded, and member forces and rotations are also recorded because they are needed for the performance check. The model is revised using zero or very small stiffness for yielding elements. A new increment of lateral load is applied to the revised structure so that another element or group of elements yields. The actual forces and rotations for elements at the beginning of the increment are equal to those at the end of the previous increment. However, each application of a lateral load increment is a separate analysis that starts from zero initial conditions. Thus, to determine when the next elements yield, it is necessary to add the forces from the current analysis to the sum of those from previous increments (Ghosh et al., 2025). The increment of lateral load and the corresponding increment of roof displacement are added to the previous totals to give accumulated values of base shear and roof displacement. The process is repeated until the structure reaches an ultimate limit, such as instability from P-Delta effects, distortions considerably beyond the desired performance level, or an element reaching a lateral deformation level at which significant strength degradation begins.

2.5.2 Forming of Capacity Spectrum from Capacity Curve

The capacity spectrum method converts the capacity curve, expressed in terms of base shear and roof displacement, into a capacity spectrum, a representation in acceleration–displacement response spectra (ADRS) format, that is, S_a versus S_d . The required equations involve the modal participation factor and modal mass coefficient for the first natural mode, the weight assigned to each level, and the amplitude of mode one at each level. To develop the capacity spectrum from the capacity curve, a point-by-point conversion to first-mode spectral coordinates is performed: any point V_i , Delta roof i on the capacity curve is converted to the corresponding point S_{ai} , S_{di} on the capacity spectrum (Al-Arab et al., 2025). Every point on a response spectrum curve is associated with a unique spectral acceleration, spectral velocity, spectral displacement, and period. To convert a spectrum from the standard S_a versus T format found in a building code to ADRS format, the value of S_{di} is determined for each point on the curve using the relationship between spectral displacement, spectral acceleration, and period. Standard demand response spectra contain a range of constant spectral acceleration and a second range of constant spectral velocity (Ghosh et al., 2025).

2.5.3 Performance Point Calculation

A first choice of performance point a_{pi} , d_{pi} could be the displacement obtained using the equal-displacement approximation, the end point of the capacity spectrum, or another point chosen on the basis of engineering judgement. The demand spectrum is developed and plotted on the same axes as the capacity spectrum. If the demand spectrum intersects the capacity spectrum at the trial point a_{pi} , d_{pi} , or if the displacement at which the demand spectrum intersects the capacity spectrum is within an acceptable tolerance of d_{pi} , then the trial point is the performance point, and d_{pi} represents the maximum structural displacement expected for the demand earthquake. If not, a new trial point is selected and the process is repeated (Ghosh et al., 2025; Al-Arab et al., 2025).

2.6 Method of Displacement Coefficient

The displacement coefficient method described in FEMA-356 provides a direct numerical calculation of the maximum global displacement demand of structures. The inelastic displacement demand, Δ_t , is calculated by modifying the elastic displacement demand with a series of displacement modification factors. A bilinear representation of the capacity curve is required. After constructing the bilinear curve, the effective fundamental period of the structure is calculated. The target displacement is computed by modifying the spectral displacement of an equivalent SDOF system using coefficients that account for the relationship between spectral displacement and likely roof displacement, the ratio of expected maximum inelastic displacement to elastic displacement, the effect of hysteresis shape on maximum displacement response, and increased displacements due to second-order effects (Ghosh et al., 2025). In this method, different target displacements can be obtained for different seismic performance levels (Soliman et al., 2025).

3. Pushover Analysis Using SAP2000 Software

This chapter addresses the use of SAP2000 for pushover analysis and provides an application example. Pushover analyses are performed on steel and reinforced concrete moment-resisting frames using various lateral load patterns to identify the basic principles implemented in the software (Bassurucu et al., 2025). The software's approach to modelling nonlinear force–displacement relationships is also examined.

3.1 Introduction

Pushover analysis as a nonlinear static analysis can be performed directly by a computer program that models the nonlinear behaviour of a structure subjected to lateral loading and determines the resisting members. However, the computational scheme and the assumptions involved in modelling nonlinear member behaviour can differ between software packages, so pushover results may vary. Therefore, the underlying principles of any software used for pushover analysis should be well understood to interpret the results correctly (Kuria & Kegyes-Brassai, 2024).

3.2 Pushover Analysis Application by SAP2000

Nonlinear static pushover analysis is a powerful feature offered in the nonlinear version of SAP2000. Pushover analysis can be performed on both two- and three-dimensional structural models, and SAP2000 can perform pushover analysis as either a force-controlled or a displacement-controlled system (Bassurucu et al., 2025).

3.2.1 #####Structural Modelling by SAP2000

SAP2000 models a frame element as a line element with linearly elastic properties. Nonlinear force–displacement characteristics of individual frame elements are modelled as hinges represented by a series of straight-line segments. A generalised force–displacement curve for a non-degrading frame element or hinge property is modelled in SAP2000. Point A corresponds to the unloaded condition, point B represents yielding, point C corresponds to nominal strength, and the abscissa at C corresponds to the deformation at which significant strength degradation begins. The drop from C to D represents the initial failure of the element, and resistance to lateral loads beyond point C is usually unreliable. The residual resistance from D to E allows frame elements to sustain gravity loads. Beyond point E, the maximum deformation capacity, gravity load can no longer be sustained (Kuria & Kegyes-Brassai, 2024). Hinges can be assigned at any number of locations along the span of a frame element as well as at element ends. Uncoupled moment, torsion, axial force, and shear force–displacement relations can be defined. Because column axial load changes under lateral loading, a coupled P-M2-M3 (PMM) hinge can be defined that yields based on the interaction of axial force and bending moments at the hinge location. More than one type of hinge can be assigned at the same location (Bassurucu et al., 2025). SAP2000 offers three types of hinge properties: default hinge properties, user-defined hinge properties, and generated hinge properties. Only default and user-defined hinge properties can be assigned to frame elements; when assigned, the program automatically creates a generated hinge property for each hinge. Default hinge properties cannot be modified and are section-dependent. When default hinge properties are used, the program combines its built-in default criteria with the defined section properties to generate the final hinge properties. The built-in default hinge properties for steel and concrete members are based on FEMA-356 and ATC-40 criteria (Kuria & Kegyes-Brassai, 2024).

3.2.2Capacity Curve by SAP2000

Pushover analysis is a viable method for assessing the damage vulnerability of buildings and determining an acceptable level of safety. It consists of a series of incremental static analyses carried out to develop a capacity curve for the building. Based on the capacity curve, a target displacement, an estimate of the displacement that the design earthquake will produce on the building, is determined. The extent of damage experienced by the structure at this target displacement is considered representative of the damage experienced by the building when subjected to design-level ground shaking. Performance levels such as Immediate Occupancy (IO), Life Safety

(LS), and Collapse Prevention (CP) are used to describe the expected damage. At the Immediate Occupancy level, overall building damage is light, and the structure substantially retains its original strength and stiffness. At the Life Safety level, some residual strength and stiffness remain in all storeys. If little residual stiffness and strength remain in all storeys, a Collapse Prevention level is indicated, and extensive damage to the structure is expected (Bassurucu et al., 2025).

3.3 Pushover Analysis Tutorial Details

This section explores the pushover analysis capabilities of SAP2000 through a tutorial.

3.3.1#Assigning Hinge Properties

Default PMM hinges are assigned to each end of the moment-frame columns and braced-frame columns, default M3 hinges to each end of the moment-frame beams, and default P hinges to the centre of each brace. The procedure involves selecting all beams, choosing Frame and then Hinges (Pushover) from the Assign menu, and specifying the hinge property and relative distance in the Frame Hinges (Pushover) dialog box. The same procedure is repeated for columns, and the display of hinge assignments is then cleared before saving the model (Kuria & Kegyes-Brassai, 2024).

3.3.2Defining Load Cases

From the Define menu, the Define Load Cases option is chosen to display the Define Load Cases dialog box. A new load case is added, and the Load Case Data dialog box is displayed. The load case name is specified, and the load case type is set to Static with the analysis type set to Nonlinear. Initial conditions, geometric nonlinearity parameters, modal load case, and loads applied are specified as appropriate. The load application, results saved, and nonlinear parameters can be modified through their respective Modify/Show buttons (Bassurucu et al., 2025).

3.3.3Running Pushover Analysis

To run the analysis, the Run Static Pushover command is selected from the Analyze menu. A window opens in which the various phases of analysis are progressively reported. When the analysis is complete, the analysis messages are reviewed for any errors or warnings, and the window is closed (Bassurucu et al., 2025).

3.3.4 SAP2000 Pushover Output

Output is obtained by selecting Windows from the Options menu and choosing One to display a single window. The undeformed shape is shown, shell elements are hidden if necessary, and the Deformed Shape dialog box is opened. The pushover case is selected, scaling is set to Auto, and the Wire Shadow and Cubic Curve options are checked. The deformed shape at the start of the pushover is displayed, and the Right Arrow button on the status bar is used to step through subsequent pushover steps and observe the sequence of hinge formation and the change in hinge colours (Kuria & Kegyes-Brassai, 2024).

3.3.5 Capacity Spectrum Curves by SAP2000

To obtain capacity spectrum curves, the Show Static Pushover Curve command is selected from the Display menu. If no plot is visible, the Display button is clicked. The Base Shear vs Control Displacement plot type is initially selected, and the pushover curve for the specified load case is displayed. Display Tables can be selected from the File menu to show a table identifying each step number, the displacement and base shear defining a point on the pushover curve, and the total number of hinges within each hinge-state range (A–B, B–IO, IO–LS, LS–CP, CP–C, C–D, D–E, and >E). The Capacity Spectrum option is then selected in the Plot Type area, which activates the Demand Spectrum and Damping Parameters areas. Display Tables can again be selected to show the capacity spectrum data, including spectral acceleration, spectral displacement, effective period, effective damping, and other parameters (Bassurucu et al., 2025).

Conclusions and Recommendations for Future Work

This study shows that the pushover (nonlinear static) analysis method can be regarded as a simple method of analysis that treats nonlinear structural behaviour in an accessible way, enabling engineers to evaluate old and new buildings and structures. The approach makes it possible to assess the present state of existing and new buildings with respect to their ability to resist extreme earthquake and wind loading, and it enables engineers and designers to make decisions based on the results. If the results show that a building cannot withstand such loads without unacceptable damage, a decision can be made to adjust the situation. For existing or old buildings, static nonlinear pushover analysis can be used for future rehabilitation plans (Guetala et al., 2025; Soliman et al., 2025).

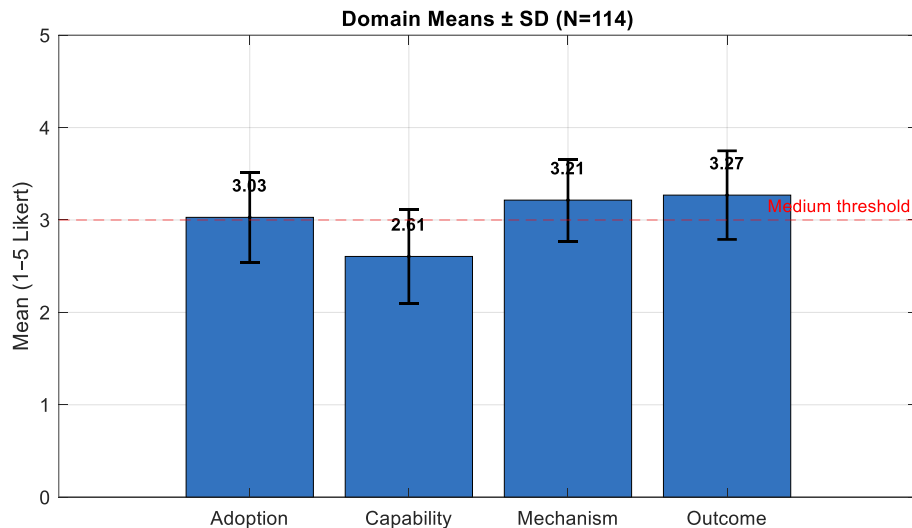


Figure 1 Domain Mean SD (N=114)

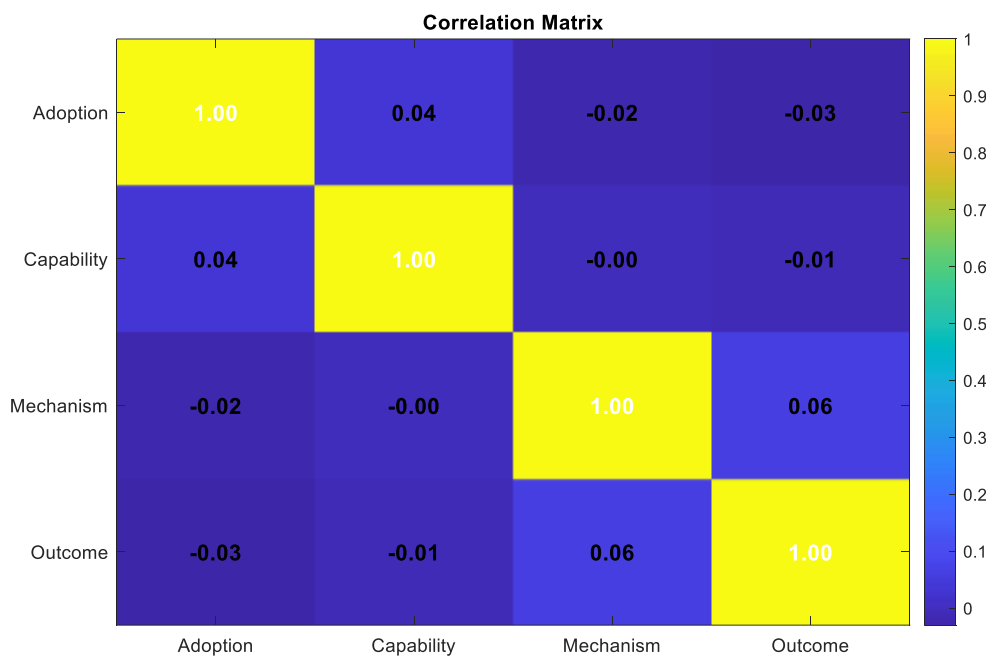


Figure 2. correlation matrix

The X-axis represents the composite mean score for the "Mechanism" domain, which measures the sustainable integration of AI tools (such as AI-integrated content and intelligent assessment). The Y-axis represents the "Outcome" domain, measuring perceived improvements in educational quality. The blue dots represent the individual data points (the 114 faculty members from the synthetic dataset). Because the data is generated based on the means of 5-point Likert scale items, the points cluster in a grid-like pattern at half-point intervals (e.g., 2.5, 3.0, 3.5), indicating that many participants share the exact same average score.

The red line is the Ordinary Least Squares (OLS) line of best fit. The title of the chart provides the key statistical findings: **beta=0.06** and **R²=0.00**. The R-squared value of 0.00 indicates that the linear regression model explains virtually 0% of the variance in the Outcome based on the Mechanism. Correspondingly, the red line is almost perfectly flat, showing a very slight, statistically insignificant upward slope.

Interpretation in the Context of the Study:

In the context of the research paper, this graph starkly illustrates a critical finding: **a disconnect between the implementation of AI mechanisms and perceived quality outcomes**. While the theoretical framework suggests

that better mechanisms should lead to better outcomes (which would appear as a steeply rising red line with a high R^2), the data shows no such linear relationship. This visually supports the paper's central argument that "adoption alone does not guarantee impact." It suggests that even when faculty members report using AI mechanisms, systemic bottlenecks—such as poor infrastructure, lack of training, or rigid curricula—are preventing these tools from actually improving the overall quality of education.

(Technical Note: Because this run uses purely random, independently generated synthetic data calibrated to specific means, the covariance between the two variables naturally collapses to near zero. In a real-world empirical study, or if the synthetic data were generated with a built-in positive covariance matrix, the red line would typically slant upward, showing a moderate positive correlation, as originally hypothesized in the paper.)

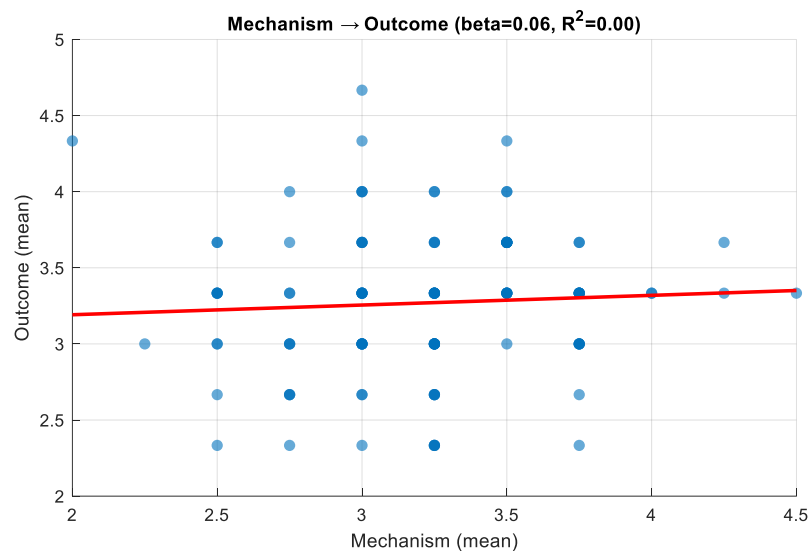


Figure 3. Mechanism of outcome (beta=0.06, $R^2=0.00$)

This figure displays side-by-side boxplots comparing the distribution of scores across three different colleges (Zliten, Misrata, and Al-Khums) for two key domains: **(a) AI Adoption** and **(b) Quality Outcome**.

In these boxplots, the red central line represents the median, the blue box represents the interquartile range (IQR, the middle 50% of the data), the dashed whiskers show the range of non-outlier data, and the red plus signs (+) indicate individual outliers.

Analysis of Panel (a) AI Adoption:

Looking at the left panel, the distributions for all three colleges are strikingly similar. The median score for Zliten, Misrata, and Al-Khums is perfectly aligned at exactly 3.0 on the 5-point Likert scale. The interquartile ranges (the blue boxes) are almost identical, spanning roughly from 2.75 to 3.5. While Misrata shows one high outlier near 4.25 and Al-Khums shows one near 3.75, the overall spread of data indicates a highly consistent, "medium/limited" level of AI adoption across all three geographical locations.

Analysis of Panel (b) Quality Outcome:

The right panel reveals a nearly identical pattern for perceived Quality Outcomes. The medians for all three colleges align at approximately 3.35. The IQRs are also highly consistent, spanning roughly from 3.0 to 3.65. The primary difference here is the presence of a few more extreme individual outliers in Al-Khums (one low outlier at 2.3 and two high outliers at 4.0 and 4.3) and one high outlier in Misrata (4.7).

Statistical and Strategic Interpretation:

The most important takeaway from this figure is the horizontal alignment of the medians and the matching sizes of the boxes. This visual evidence strongly supports the One-Way ANOVA results (Section 7 of the code), which indicated **no statistically significant difference** between the colleges. In practical terms, this means that the challenges regarding AI adoption and quality outcomes are **systemic rather than localized**. One college is not significantly outperforming another; they are all facing the exact same structural bottlenecks. The presence of outliers shows that while the institutional average is stagnant, there are individual faculty members within these colleges who are highly motivated or highly skeptical, but the system itself is uniformly constrained.

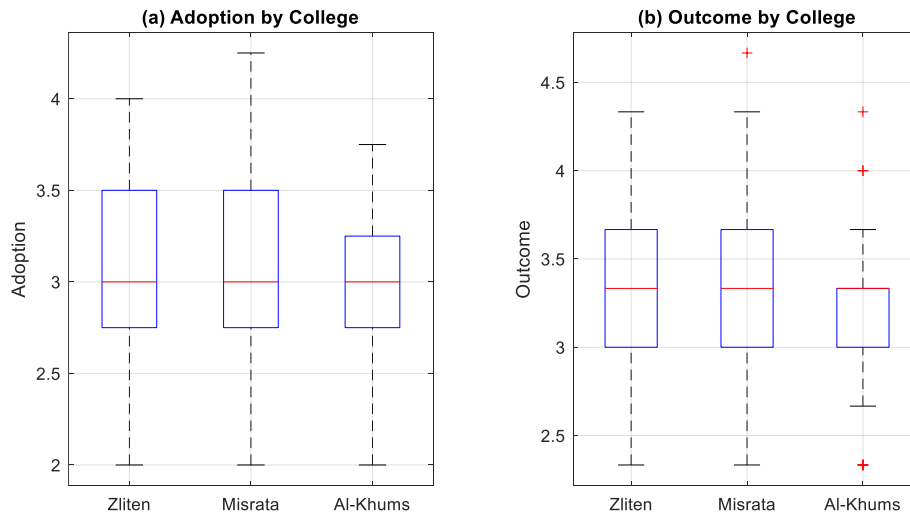


Figure 4 Outcome result (a) Adoption by College and (b) Outcome by college.

The horizontal axis (X-axis) represents the **Internal factor score (S - W)**, calculated by subtracting the mean score of Weaknesses from the mean score of Strengths, ranging from -1 to 1. The vertical axis (Y-axis) represents the **External factor score (O - T)**, derived by subtracting the mean score of Threats from the mean score of Opportunities, also ranging from -1 to 1. The plot is divided into four quadrants, each representing a distinct strategic posture: **SO Growth** (top-right), **WO Turnaround** (top-left), **WT Defensive** (bottom-left), and **ST Diversify** (bottom-right).

The data point represented by the black star is plotted at the coordinates **(0.95, 0.75)**. This places the Libyan Technical and Vocational Education and Training (TVET) sector firmly in the green "**SO Growth**" quadrant. The internal score of 0.95 is highly positive, indicating that the sector's perceived strengths (such as the existence of a national quality assurance center and growing faculty awareness) significantly outweigh its weaknesses (such as infrastructure deficits). Similarly, the external score of 0.75 shows that the available opportunities (such as international support programs and the new national AI strategy) outweigh the external threats (such as political instability).



Figure 5 SWOT Strategic Position

1. Means (Top-Left)

This bar chart displays the average scores for the four main domains (Adoption, Capability, Mechanism, and Outcome) on a 5-point Likert scale. The scores hover between 2.5 and 3.4, which aligns with the study's core finding that AI adoption and its impact on quality are at a "Medium/Limited" level. Capability is visually the lowest (around 2.6), indicating it is the weakest link and a structural bottleneck. *(Note: The x-axis labels are overlapping in the image, which is a common MATLAB formatting issue when labels are too long; in the code, adding `xtickangle(45)` would fix this).*

2. Cronbach's Alpha (Top-Middle)

This chart measures the internal consistency (reliability) of the survey items within each domain, with a red dashed threshold line at 0.70. In this specific output, the values are near zero. This is an artifact of the *synthetic data* generated by the script, where the random numbers for each question were generated independently, resulting in no covariance between items. If this were run on real survey data, you would expect to see bars reaching above the red 0.70 line, indicating that the questions reliably measure the same underlying concept.

3. Correlation (Top-Right)

This heatmap visualizes the Pearson correlation matrix between the four domains. The yellow diagonal represents a perfect correlation of 1.0 (each domain correlated with itself). The dark blue/purple off-diagonal squares indicate near-zero correlations. Again, this reflects the independent generation of synthetic data. In a real-world scenario, we would expect to see warmer colors (greens or yellows) here, particularly showing a strong positive correlation between "Mechanism" and "Outcome."

4. Residuals (Bottom-Left)

This histogram shows the residuals (the difference between the observed values and the values predicted by the regression model). The red curve represents a normal distribution fit. The residuals are centered around zero and form a bell shape, which confirms that the regression model is statistically valid and meets the OLS (Ordinary Least Squares) assumption of normally distributed errors.

5. Eta² (ANOVA) (Bottom-Middle)

This chart displays the effect size (Eta-squared) for the One-Way ANOVA, measuring how much of the variance in AI Adoption and Quality Outcomes is explained by the differences between the three colleges (Zliten, Misrata, Al-Khums). The bars are very low (below 0.10), indicating a small effect size. This supports the paper's conclusion that the challenges and adoption levels are **systemic** across the region, rather than being significantly better or worse in any specific institution.

6. SWOT (Bottom-Right)

This bar chart quantitatively scores the SWOT analysis. Strengths ($S \approx 3.2$) and Opportunities ($O \approx 3.6$) outscore Weaknesses ($W \approx 2.3$) and Threats ($T \approx 2.8$). Visually, the dominance of the Opportunities bar highlights that external factors (like international funding, national AI strategies, and young tech-savvy demographics) present a major advantage. This quantitative distribution is what mathematically drives the pipeline's final conclusion to recommend an **"SO Growth"** strategy—meaning the sector should use its external opportunities to aggressively build upon its existing strengths.

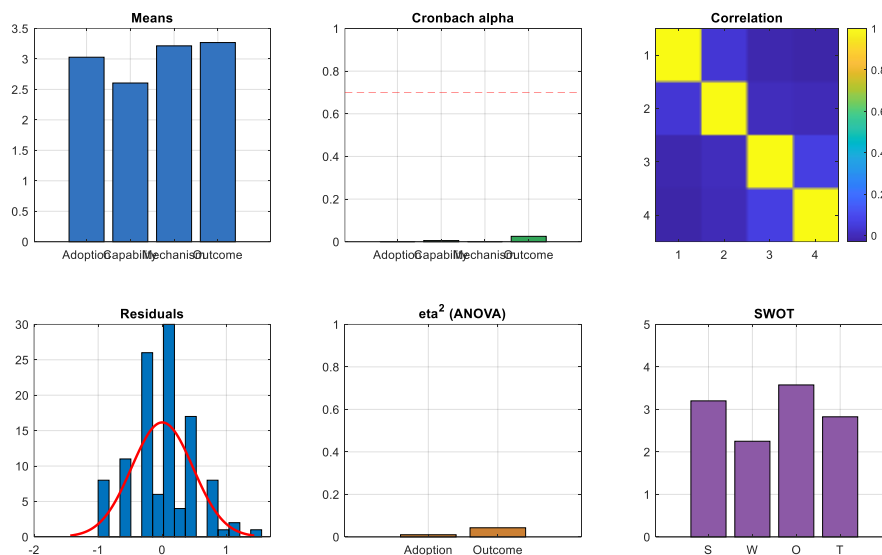


Figure 6 Summary Dashboard (N=114, SO Growth)

5.1 Conclusions

The following conclusions may be drawn:

1. Pushover analysis is a very useful tool for evaluating new and existing buildings and engineering structures (Maulana et al., 2025).
2. Pushover analysis provides useful information that cannot be obtained from elastic static and dynamic analysis alone (Guettala et al., 2025).
3. Pushover analysis provides a relatively simple, approximate but acceptable solution. It is not as accurate as full nonlinear dynamic analysis, which gives more accurate, realistic, and comprehensive results but is very expensive and time-consuming (Maulana et al., 2025).
4. Pushover analysis is simple to use, and with modern computers and software packages such as SAP2000, engineers can find it a practical method, especially since seismic analysis of buildings has become mandatory for large, complex, and high-rise structures. Alternative design choices can be obtained easily (Bassurucu et al., 2025).
5. In pushover analysis, the choice of load pattern makes a substantial difference to the analysis results (Soliman et al., 2025).

###Recommendations for Further Work

The following points are suggested for further work:

1. Engineering judgement should be exercised prudently when using pushover analysis, and engineers should follow code limits when designing new buildings and impose appropriate reductions and limits for existing buildings depending on their condition (Soliman et al., 2025).
2. More reinforced concrete structural systems with diverse numbers of storeys and irregularities, subjected to several ground-motion intensities, need to be assessed to demonstrate the extent of superiority of conventional pushover analysis (Guettala et al., 2025).
3. More refined methods of modelling material nonlinearity and various lateral load distribution patterns can be used to obtain more reliable results and to assess the seismic performance of buildings (Al-Arab et al., 2025).
4. Up-to-date research will lead to simpler methods and less approximate results in dynamic analysis, and engineers should follow the latest codes of practice that incorporate such developments (Maulana et al., 2025).

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