論 文 の 内 容 の 要 旨

論文題目　鉄筋コンクリート柱の軸崩壊過程と補強手法に関する実験と解析

Experimental and Analytical Study on Axial Load Collapse Assessment and Retrofit of Reinforced Concrete Columns

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Abstract

The major objective of seismic design has been the improvement of structural performance of construction through damage control and protection against collapse. While damage control has been well documented and various methods and studies have been achieved, collapse mechanisms have been found complex and are still not well understood. Experimental research and post-earthquake reconnaissance have identified that reinforced concrete columns with light or widely spaced transverse reinforcement, particularly short columns, are susceptible to shear failure during earthquakes. Although the process is not well understood, a reduction in the axial load capacity of a shear-damaged element induces automatically a transfer of its carried gravity loads to neighboring elements, possibly leading to a progression of damage, and sequentially, collapse of the structure. However, reconnaissance of recent earthquakes confirmed that structural elements can experience significant damage, including shear failures and loss of axial load capacity, without collapse of the entire building system. This fact indicates that the entire system should be considered when evaluating the collapse limit state. To do so, a system-based capacity assessment by mean of appropriate analytical models incorporating the shear and axial load failure of reinforced concrete columns are required.

Collapse of structures or structural elements under gravity loads during earthquakes may result from a multifaceted interaction between the lateral demands required by the strong motion, the vertical demands required by the structure’s weight and by the vertical action resulting from overturning, the lateral capacity of the structural resisting system, and the vertical capacity of the structural elements or the system to hold the gravity loads. If the lateral demand causes degradation in the lateral capacity, which in turn leads the vertical capacity degrading below the level of the vertical demand, the structure or the structural elements become unable to sustain the gravity loads and consequently collapse. To capture such multiple interactions between lateral and vertical capacities collapse mechanisms should be well grasped. To do so, the separation of the combined effects and phenomena would be the first step of understanding the complete process. Then, analytical and more experimental research are required to develop appropriate analytical shear and axial load capacity models for existing reinforced concrete columns that would catch their factual behavior under

various loading patterns and would be implemented easily through a simple analytical model for engineering applications. Adjusting these models needs various experimental tests and careful observations on damaged or undamaged structures during post-earthquake investigations.

Given the present state of knowledge and the lack of understanding of how axial loads will be supported after a certain level of damage, principally after shear failure, some engineers and specialists involved in the seismic retrofit of structures have advised not protect all elements from failure during strong shakings due to economic reasons, while some others have recommended use of secondary gravity load support systems to ensure safety against a total collapse of concerned structures. However, locally, insufficient or fragile columns must be dealt with and their problems must be solved in order to prevent their collapse and consequently the loss of lives and goods.

Actually, to reach a decision to retrofit such structures involves many factors, particularly the importance of the premises (ground, building, location, etc.), the interruption time limit and the cost of the selected operation to upgrade the existing structure to a certain chosen level.

The existing solutions to cure such problems and improve the performances of these elements are not abundant. However, the most chosen solution in many cases is the strengthening of the whole structure or a part of it. Different methods may be suggested to proceed to such strengthening. The weak or non-ductile structures that possibly fail to sustain seismic loads may be rehabilitated by inserting steel frames that help reduce the loads on the existing structures and elements but the added elements may congest the space, making the solution somehow problematic. Another way is to intervene locally. The fragile columns that possibly fail in a brittle manner may be rehabilitated by enveloping them externally in a way to confine their concrete. Such confinement allows reaching larger deformations by preventing the opening of large cracks that lead to rupture. Such envelopes, being of concrete or steel, were developed and confirmed experimentally but appear to be a costly process and time consuming. Although the structural efficiency of steel envelopes, the corrosion problem and the difficulties faced during the installation of the plates pushed the engineers to elaborate other solutions. Later research studies suggested that steel jackets may easily be replaced by composite materials and by the way eliminates the problem of corrosion and simplify the construction work. By their very high ratio resistance/weight, their remarkable resistance to environment aggressive factors and to fatigue, their availability in various forms and lengths, as well as their quick and easy implementation, the composite materials seemed very ideal for external application and appeared very clearly as the solution to various faced problems. Therefore, their purchasing cost and the need for a specialized labor to implement them make the retrofit process expensive.

To reduce the time and the cost of the retrofit process, new materials and procedures should be explored and then tested to judge of their applicability and efficiency. To do so, first, experimental research is required to develop appropriate analytical models for retrofitted reinforced concrete columns that would catch their factual behavior under various loading patterns and would be implemented easily through a simple analytical model for engineering applications.

The first experimental work described in this document was carried out on reinforced concrete columns, particularly shear-critical ones, in order to investigate their behavior beyond shear failure till full collapse under vertical loadings during earthquake events and to identify the probable collapse mechanisms. The achieved quasi-static test programs revealed that collapse under the applied axial loads, being constant or varying, and under different lateral loading types, being cyclic with high frequency or cyclic with low frequency or monotonic, occurs when the shear strength becomes negligible. The shear degradation from the peak till the moment of collapse follows generally two slopes changing at almost the same lateral drift ratio of 2%. The lateral deformability of columns can reach large values before collapse. In the contrary to what is generally spread, beyond shear failure columns under varying axial loads that may reach very high values can perform better than or at least similarly to columns under constant and moderate axial loads. Although only tow columns were tested under varying axial loads, it is confirmed that columns can sustain very high axial loads at small lateral drifts, therefore, the degradation of the axial capacity increases with increasing lateral loading.

The analytical work described in this document suggests simple procedures to evaluate the shear strength, the lateral drift at shear failure and the lateral drift at axial failure. While the procedure to evaluate the lateral drift at shear failure is based only on an analysis of a database containing a set of 83 shear-critical reinforced concrete columns, the procedure to evaluate the shear strength and the lateral drift at axial failure is based on an analytical approach propped by a database containing a set of 43 shear-critical reinforced concrete columns. The mentioned databases are gathered from literature and contain the data of the tested columns, which are presented in the experimental work.

To evaluate the shear strength of shear-critical columns, the theory of fracture mechanics is applied in parallel to the truss model. The shear strength is considered composed of two blocs. The first bloc is evaluated by the truss model while the second bloc is evaluated by modification of a basic expression of the concrete tensile strength component. A comparison of the shear strength evaluated by the mentioned procedure to some other existing practical methods (Arakawa, AIJ) reveals the appropriateness of the suggested procedure. A simple statistical analysis of the columns of the database that assesses the dispersion of the evaluated values around their mean value gives relatively fair results compared to other procedures.

To evaluate the lateral drift at shear failure, review and examination of previous existing methods through the selected database directed the analysis. The main influencing intrinsic parameters of reinforced concrete columns are used in the analysis of the database. A simple expression with a minimum limit and that includes the transverse steel ratio and the normalized shear stress is suggested for the evaluation of the lateral drift at shear failure. A simple statistical analysis of the columns of the database that assesses the dispersion of the evaluated values around their mean value gives relatively fair results compared to other procedures.

To evaluate the lateral drift at axial failure, review and examination of previous existing methods, though limited, through the selected database and the observations made during the implementation of the test programs helped to direct the analysis. The theory of fracture mechanics is applied also for this part in parallel to the truss model. First, identification of the appropriate failure mechanism is achieved after determination of the size of the fracture band in the truss model. Some parameters from the database are used in order to decide about the expected mechanism. A simple equation is suggested as to the failure mode. Two mechanisms are suggested to evaluate the lateral drift at axial failure. The first mechanism, based on shear friction assumptions, is supposed to act along an oblique dominant crack on the section height of columns. The second mechanism, based on development of plastic hinges at two sides of longitudinal steel bars, is supposed to act on an oblique cracked region on the section height of columns. Simple expressions are suggested for both mechanisms in order to evaluate the lateral drift at axial load failure. Comparisons of the analytical values to the test results and their dispersion around their mean value by statistical analysis using the database of 43 columns shows some improvements compared to the results obtained from previous methods. Finally, based on the values of the lateral drift at shear failure and axial failure, and the observation made on the obtained response of the shear-critical columns, a model for the response envelope curve is suggested. Although some discrepancies, the proposed model appears close to the actual responses and could be more appreciated if more data were available.

The second experimental work described in this document was carried out on retrofitted reinforced concrete columns, similar to the shear-critical bare columns presented in the first part before, in order to investigate the effect of a new-applied composite material wrapped on such seismically-insufficient columns and evaluate their behavior till large lateral drifts under vertical loadings during earthquake events and to identify the parameters that can be considered to design the necessary envelope for a desired level of performance. The achieved quasi-static test programs revealed that the assigned confinement is very effective and brings to the columns a large lateral deformation capacity with a slight increase in shear strength compared to their bare similar columns.

Simple expressions, based on the proposed equations for shear strength and lateral drift evaluation and on the existing expressions of Arakawa or AIJ, are suggested in order to evaluate the strength of the confined columns. The first procedure suggests the direct substitution of any of the adequate equations for the evaluation of shear strength for bare elements into the shear degradation expression developed for the new-applied material. The second procedure suggests the use of an appropriate existing equation for shear strength evaluation and substituting the term containing the transverse steel ratio by an equivalent term that contains both the transverse steel ratio and the transverse confinement material ratio. Comparison of the evaluated shear strengths to the test results shows that the application of these procedures gives acceptable results and allows the prediction of the shear strength brought by the provided amount of confinement.

Another simple procedure, similar to the one made previously for bare elements which are assumed experiencing region failure collapse, is suggested to evaluate the axial failure and the corresponding lateral drift for retrofitted columns. At this step, while the procedure, compared to test results, reaches good results for slightly confined columns, it overestimates them for considerably confined columns. More detailed analyses are required in the future.

Furthermore, simulation of the response of retrofitted columns using the fiber model analysis by a computer program (CANNY-99) allows generally reaching relatively fair general responses in terms of shear strength till a certain level of lateral drift. Shear and stiffness degradation are simulated through a set of parameters that should be adjusted for both concrete and steel and for each column. As to the envelope curves for the material, while the one of steel is considered of tri-linear type and considered as conform as possible to the test results on steel bars, the concrete envelope curve is evaluated from test results carried out on confined cylinders and prisms, which the behavior under axial loading shows a parabolic increase in the axial stress from a certain level of axial strain. Based on the test data on a set of confined cylinders and prisms, a simple expression is suggested to evaluate the stress of confined element with the new-applied material. The application of the expression allows reaching, generally, acceptable results and predicting, till a certain level of lateral drift, fairly the response of the confined shear-critical reinforced concrete columns.