論文の内容の要旨

論文題目　Seismic performance of non-structural precast concrete walls in RC buildings

「鉄筋コンクリート造建物におけるプレキャストコンクリート非構造壁の
耐震性能に関する研究」

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Buildings consist of both structural and non-structural components. A wall is considered non-structural when it is not intended to participate in resistance to the lateral forces. Using current methods of analysis, predicted response of a building to an earthquake excitation is considered to be the response of the bare frame only. Internal constructions, such as partitions, are ignored. This is the case if wall is isolated. However, for the precast concrete (PCa) partitions, isolation is physically impossible due to existing connector elements at the interface. Characteristics of joints and primary system will determine the degree of interaction. Although, much research has been carried on the structural safety of RC buildings under seismic loading, behavior of PCa walls and their interaction with primary system has received little attention.

In the scope of this study, the question of how and in what condition, a PCa panel wall can alter building behavior have been tried to answer. This makes PCa partition walls is no longer non-structural but necessitates integrating into design models. Quantifying non-structural effects on building response is important for currently developing Performance Based Design (PBD) codes. Because, the key is that the performance is based on facility performance and not just structural. The research program includes numerical modeling, experimental works, verification of analytical model with test data, parametric study on affecting factors and finally proposing simplified design approaches for the non-structural PCa jointed walls as an alternative tool for engineers in practice.

In Chapter 1, general considerations about non-structural members, their classification due to functionality and response sensitivity are explained. The dual response mechanisms of PCa elements jointed to the frame with dowel bars is introduced and the possibility of considering them as an alternative (cheap) passive control system in building design and/or even strengthening works are indicated. Then, motivation and objectives of proposed study is shown by telling the current ignorance of non-structural effects in practice. Finally, the organization of the thesis is given.

In Chapter 2, past research and literature review for the problem of concern, different solutions considered in the past for evaluating architectural walls are discussed and their problems are indicated. Analytical and experimental studies on the seismic performance of non-structural components, in general, have been scarce and not significantly influenced the development of codes. So, in the frame work of this study, the problems were stated and several aspects of them were investigated independently. In most cases, it necessitated a comprehensive interdisciplinary literature survey. Because, there have been no similar studies performed so far in the field of RC structures.

In Chapter 3, nonlinear behavior of dowel type connectors is discussed. Failure criterion, theoretical and existing empirical capacity formulations which were proposed by different researchers is explained. Factors effecting dowel behavior are determined and further used as being key parameters in the experimental program. In the past, there were studies regarding the modeling dowel action for reinforcing bars in concrete members. These studies were limited to interaction free conditions and so far there have been no studies performed specially for PCa panel elements. In the case of PCa, problem of concern is in macro level and the structural system, loading conditions are completely different from a single monolithic member. This necessitates performing an experimental program in order to build up proper knowledge for the nonlinear dowel modeling.

In Chapter 4, an experimental program for the response evaluation of PCa panels jointed with dowels is explained by providing information regarding to frame set-up, loading history, test parameters, specimen details, and measurement system. This experimental study is unique from several perspectives and going to be pioneer in the field of seismic resistant design. It was performed at the Shimizu Institute of Technology Laboratories from June to July, 2005. A portal frame model of 8-story R/C residential building which is commonly used in Japanese practice was selected as prototype for the specimens. Specimens and loading frame are all full scaled in order to establish realistic database. Several parameters like panel size, gap distance, connector type, attachment configuration and bounding conditions were investigated with total 7 specimens. The experimental verification will be in the progressive steps of clarifying interaction effects on dowel behavior, resistance and energy dissipation due to connectors, failure pattern, and then finally will be the detection of contact action.

In Chapter 5, calibration test program is introduced. In the earlier panel test 5 equally spaced tri-axial strain gages attached at each joint for use in deriving major force components generated on individual connectors. The calibration test is performed using same joints by creating known forces on them. By this way, reliability of the records can be checked. The results proved the energy loss due to friction while transferring forces between the dowel and joint plates. It causes underestimation of calculated forces on connectors. Other factor is that the increase in overlapping distance between the dowel plate edge and gage attachment line, cause additional energy loss which is resulted with increase in calibration ratios. Average calibration ratios for shear forces obtained from tested joints have a range from 1.8 to 3.5. Other factors such as applied torque level on bolts also investigated. By employing combination of several affecting factors, the most possible closeness reached between expected and measured results was a ratio around 1.25

In Chapter 6, results of the panel test were evaluated. Inhere, measured force-displacement loops, comparison among the hysteretic response curves, ductility, cyclic degradation and energy calculations were performed. The results can be summarized as follows; (1) In general, connectors show significant energy dissipation with increase in story drifts, and effective at small drift range (2) Upper connectors prone to higher resistance and energy dissipation (fat loop) relative to bottom ones, (3) Failure mode of dowel bars at all specimens was similar fatigue type at the top plate joint, (4) Specimens B1 and B4 (deformed bar) reaches failure state before a major event (<1.0% drift - safety risk), (5) Highest strength and cumulative energy was recorded for specimen A1 due to existence of side connector, (6) Unbounded bars (B3) allow a shift in performance for larger drift values (no force coupling), (7) The strength degradation started when the concrete cracks develop at around 0.25% for all B and A series except B3, (8) Introducing smaller gap distance (B4) causes a significant increase in initial stiffness and strength (34%), however no effects seen at cyclic energy, (9) Ultra mild high elongation plain bars (B2) increase the deformability and level of failure state approximately two times compare to the normal deformed bars, (10) Both specimen C1 and C2 (slim panels) remained stable until high drift values, but their resistance contributions are low.

In Chapter 7, individual connector response calculation is performed by combining the recorded strain gage data and calibration results. Rosette gage theory and force equilibrium were applied for the derivation of major force components on joints. Failure criteria for dowel connectors are also studied using CDP measurements during the panel test. Following remarks are made; (1) in similar conditions, the difference between a normal deformed bar (B1) and a high elongation bar (B2) is that; (a) normal deformed bar mainly failed by shear with %50 strain (only 2% axial strain). (b) However, a low yield smooth bar fails by the coupling of shear (%65) and tension (21%), (2) For the deformed bars, the higher the axial strain rates, smaller the shear strain capacity at failure stage. For top connectors A1, the failure occurred by coupling when the shear strain is around 25% to 37 %, and axial strain is from 15% to 18%., (3) Due to unbonding conditions, specimen B3 gone higher shear strain values up to 95%. Because, no axial strain generated on the connectors of this specimen.

In Chapter 8, an analytical model suitable for representing non-structural PCa jointed walls in nonlinear frame analysis is proposed and later reliability of them with experimental results are shown. Limitations and applicability of the proposed model are discussed. For the verification, two approaches were considered. (1) First one is called as implicit approach. Effects directly integrated without any assumption, but using tri-linear hysteretic parameters taken from individual response curves. In general, strength envelopes were fairly estimated with an average value of strength ratio between simulation and measured records at cycle peaks is 1.10. So, proposed discrete spring (DS) model and analysis routine partially proved that it looks adequate for representing PCa partitions in structural analysis. (2) Second one is called as empirical approach. In here, dowel capacity envelope and interaction effects were assumed using appropriate formulas. Then, it was combined with Bouch-Wen type non-linear modeling rules. This is important for simulating arbitrary conditions for panel and dowels. In this approach, strength envelopes were over-estimated with an average value from1.20 to1.40. The reasons mainly come from difficulty of representing cyclic degradation.

In Chapter 9, a parametric study is performed to investigate the factors influencing nonlinear response of PCa panel walls in arbitrary conditions. Degree of dependency of parameters to the overall response is also discussed. Following remarks are made; (1) The increase in material strengths cause increase in stiffness and strength, but a slight decrease in yielding displacements, (2) However, increase in diameter size, not only increase the strength but also extends the yielding displacement beyond higher values, (3) By keeping the total connector steel area same, it is preferable to use bigger diameter size. Even if the shear capacity does not change much, the deformability performance (ductility) increases, (4) Value of the decrease in dowel strength due to increase in gap distance is smaller for larger bar diameters, (5) Yielding displacement increases together with the increase in bar diameter and increase in gap distance, (6) Smaller edge distance cause rapid increase on tension forces on dowels results with sharp decrease in dowel capacity and early failure, (7) Common practice of using two deformed bar attached to panel edges is a safety risk to the human occupants (failure before a major event). For practice, it is recommended using minimum 3-D13 with one of them being at the mid of the panel.

In Chapter 10, simplified design concepts like equivalent viscous damping ratio, non-structural effects on surrounding frames, and design of panel wall are investigated in detail. It has found that non-structural panels can be a promising energy dissipation device for seismic event with equivalent damping ratio of 2 to 3% at story drift level of 1.0% if provided in a typical six-story reinforced concrete moment frame building designed with Ds factor of 0.3. It has also showed the possibility of calculating minimum connector number and size to reach the target damping ratio at each story. When detailing the wall panels with reinforcing steel connectors, the amount should be less than those required to resist the cracking moment of the wall section. Design methodology is proposed by a diagram under combined loading conditions of flexure and shear, pure tension and shear. Finally, non-structural effects on design of column and beam members were investigated. A simple procedure for the shear design was introduced. The results prove that the non-structural effects on beam elements should be treated carefully. Especially, when there is need for higher performance requirements. The attachment location at the beam hinging zone will require special detailing in that case.

In Chapter 11, main outcome of the experimental and numerical investigations carried out in this research are summarized. Important conclusions are highlighted and core needs for future studies are identified.