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Investigating and Modeling the Effect of Using High-strength Concrete on the Behavior of Structures During Earthquakes

Investigación y Modelado del Efecto del Uso de Hormigón de Alta Resistencia en el Comportamiento de las Estructuras Durante los Terremotos

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ABSTRACT

One of the issues that most cities in the world are dealing with is the issue of natural disasters. Therefore, it is necessary to carry out detailed studies to identify the sources of earthquakes with the possibility of producing long-lasting earthquakes in Iran, and the effects of durability on reducing the resistance of structures should be taken into account when designing. This issue may not only cause damage to structures in high-durability earthquakes, but also can lead to their damage in the event of relatively strong aftershocks. Considering the importance of earthquake resistance of buildings in seismic areas, improvement of concrete properties has a special place. Currently, based on the common technology of concrete, the production of concrete with high compressive strength is far from expected to be used for the design of common functional structures.

Keywords: high strength concrete, earthquake, compressive strength, tensile strength.

RESUMEN

Uno de los problemas a los que se enfrentan la mayoría de las ciudades del mundo es el tema de los desastres naturales. Por lo tanto, es necesario realizar estudios detallados para identificar las fuentes de terremotos con la posibilidad de producir terremotos de larga duración en Irán, y los efectos de la durabilidad en la reducción de la resistencia de las estructuras deben tenerse en cuenta al diseñar. Este problema no solo puede causar daños a las estructuras en terremotos de alta duración, sino que también puede provocar daños en el caso de réplicas relativamente fuertes. Considerando la importancia de la resistencia sísmica de los edificios en áreas sísmicas, la mejora de las propiedades del concreto tiene un lugar especial. Actualmente, basado en la tecnología común del hormigón, la producción de hormigón con alta resistencia a la compresión está lejos de ser utilizada para el diseño de estructuras funcionales comunes.

Palabras clave: hormigón de alta resistencia, sismo, resistencia a compresión, resistencia a tracción.

1. INTRODUCTION

One of the issues that most cities in the world are dealing with is the issue of natural disasters. Natural disasters (especially earthquakes), which are often silent but potentially prone to damage, cause an average of more than 150,000 deaths and more than 140 billion dollars in financial losses in countries, especially developing countries, annually. In the meantime, Iran is one of the accident-prone countries in the world, as in the past few decades (Buin Zahra earthquake, 1963 to Bam earthquake, 2003) due to the occurrence of such incidents, it has suffered a lot of damage (life and financial).

The duration of strong movements of the earth has a significant effect on the amount of damage caused by earthquakes to buildings. Many physical processes, such as reducing the hardness and resistance of all types of structures, depend on the number of load or stress cycles that occur during an earthquake. A movement with a short duration, even if it has a large range, may not cause enough cycles to reach the structure. On the other hand, a movement with medium amplitude but long duration will create enough load cycles to cause damage in the structures. Earth tremors produced by large and high-intensity events and reports recorded in locations far from the epicenter are all reminders of long earthquake durations. Therefore, the structures built in these areas must have the bearing capacity against long-term ground disturbances, according to the soil conditions of the construction site (Ahmadi, 2013).

The duration of the earthquake is directly related to the magnitude of the earthquake. On the other hand, many researchers have studied the relationship between the damage of structures and the duration of strong ground motion. Chai et al. have suggested that a larger ground motion period increases the base shear of the inelastic design. Despite the various studies to investigate the characteristics of the durability of strong ground motion and the existence of several different definitions of the durability, there is still a need for more studies related to the effect of earthquake durability on structures. Failure to consider durability in seismic design regulations has become a reason for paying relatively little attention to prediction equations for durability compared to damping equations for spectral accelerations. FEMA Guideline 440 has provided updated information on the modeling of structures including reinforced concrete buildings by considering stiffness deterioration, strength reduction and nonlinear dynamic response. In a research, three-dimensional hardness deterioration and strength reduction have been investigated considering the progressive failure of reinforced concrete structures. It should be added that the durability of earthquakes has been investigated in the form of the effects of successive earthquakes and aftershocks on structures. In addition to experimental and theoretical simulation models, the reduction of resistance and hardness due to real consecutive earthquakes has also been investigated on reinforced concrete structures (Hamdi, 2015).

2. LITERATURE REVIEW

Sadjad et al. (2007) mentioned that seismic performance can be assessed for lateral load resistance, classification of yielding of the members, and distribution of inter-story drift. A typical 5-story frame is developed as ductile, nominally ductile, GLD, and retrofitted GLD in this project. It provides an analytical approach for the seismic evaluation of RC frames with the help of nonlinear time-history analysis and momentum over analysis. These analytical models are authenticated against accessible experimental results. Along with this, a study was conducted to assess the seismic behavior of these 5-storey frames. To sum up the discussion, one could say that the ductile and nominally ductile frames behaved well under the influence of the considered earthquake; on the other hand, the seismic performance of the GLD structure was not sufficient. The seismic performance was enhanced when a modification of the damaged GLD was undertaken. Moreover, the seismic performance of a twelve-story reinforced concrete moment-resisting frame structure along with shear walls with the help of 3D finite element models was presented by Sea et al. (2015) , in accordance with seismic design regulations based on the Federal Emergency Management Agency (FEMA) recommendations and seismic building codes together with the Los Angeles Tall Building Structural Design Council (LATBSDC) code.

In addition, the seismic performance of reinforced concrete frame was assessed using the capacity spectrum method. Değer et al.(2015) opted to associate the seismic performance of two 42-story reinforced concrete buildings located in Los Angeles, California. One was a combined core wall building and the other was a comparable core wall building with perimeter moment-resisting frames (i.e., dual system). Two different approaches were introduced to design the buildings. The first approach followed the traditional code prescriptive design approach as mentioned in the International Building Code (2006). On the other hand, the second approach followed a performance-based design approach that was aligned with the seismic design guideline published by the Pacific Earthquake Engineering Research Center. These two systems were modeled with detailed finite element methods, resulting in different design approaches. To assess the seismic performance of the sample model at five dissimilar earthquake shaking intensities, these models are used.

Chandramohan (2016) surveyed the influence of structural collapse risk and the integration in the design and assessment practices. The broad objective of this study was to evaluate the influence of ground motion duration on the structural collapse risk, and it was found to be significant to propose methods to consider for the performance assessment and design of structures.

An experimental study on corroded RC moment-resisting frames was performed to study the effect of longitudinal reinforcement corrosion on the seismic behavior of RC frames by Liu et al. (2017). An experiment was conducted on six frame specimens, five of which were corroded and one of which was not. The specimens were loaded with quasi-static cyclic forces for a period of three weeks after loading. The corrosion ratio of longitudinal reinforcement and the axial compression ratio were appraised to be the most important variables. The results showed that, with an increase in the corrosion ratio, the lateral load carrying capacity and the deformation capacity of RC frames decreased roughly linearly, and the energy dissipation capacity minimized approximately exponentially. For corroded frames with low axial compressive load level, the lateral strength and the energy dissipation capacity were enhanced with an increase in the axial compression ratio, and the effect of the axial compression ratio on the deformation capacity was insignificant. During the loading process, the frames with increased corrosion ratio or axial compression faced significantly more destructions at the beam ends. The damage evolution of the columns was not affected enough by the corrosion ratio and the axial compression ratio compared to the beam.

Furthermore, the study by Daei et al. (2022) quantified the effects of pulse-like near-fault ground motions on reinforced concrete moment-resisting frames (MRFs) in order to compare the results to those induced by non-pulse-like ground motions. Accordingly, three archetype buildings with 3-, 9-, and 18-story heights were designed and subjected to 48 ground motions in four sets that included forward-directivity, fling-step, non-pulse near-fault, and far-fault motions. In addition, compared to pulse-like ground motions, non-pulse-like motions showed significantly higher contributions from higher modes to the seismic responses. A pulse-like ground motion also imposed a higher maximum seismic demand than a non-pulse-like motion.

By installing self-centering braces on SMRFs, Hu et al. (2022) proposed a peak and residual displacement-based design (PRDBD) method to control the peak and residual inter-story drift. According to the proposed PRDBD method, peak displacements and residual displacements served as the design targets. A machine learning prediction model was developed, based on the median response of a single-degree-of-freedom system, to determine the inelastic and residual displacement ratios during earthquakes. It was discussed in detail the steps involved in the design of the PRDBD method. Retrofitting three- and nine-story demonstration buildings was achieved using the PRDBD. Here, two different design targets were used.

Static and dynamic analyses were used to corroborate the efficiency of the proposed PRDBD method. The results of the static analysis showed that the self-centering braces could effectively improve a SMRF's stiffness and strength. The retrofitted SMRFs presented no strength deterioration, and the original SMRFs presented obvious strength deterioration at the roof drifts of 3.2% and 2.5% in the three- and nine-story buildings, respectively. On the other hand, Cao et al. (2022) highlighted an external substructure designed to improve the seismic performance of existing frame buildings, namely the post-tensioned precast bolt-connected steel-plate reinforced concrete frame (PT-PBSPC frame). It involved the introduction of the mechanism and the design of a sub-structure, and pseudo-static experiments were performed on the basis of four scaled frames to demonstrate the technical details (e.g., precast or monolithic, and with or without prestress) and the macro responses (e.g., failure patterns, hysteresis curves, strain developments, and self-centering capacities). In order to clarify the distinct varying tendency and appropriate detail selection, the simulation model as verified by experiments was presented and the numerical elements and materials were compared, in addition to extending an experimental work that involved a detailed parametric study with different controlling parameters. As a general conclusion, the precast assembly had an equal performance to the monolithic specimen.

Fazileh et al. (2022) explained the seismic performance of this system using the FEMA P695 methodology. For this purpose, by using nonlinear static and dynamic analyses, many different archetype configurations were developed and analyzed. According to the results of the performance assessment, the CSA and NBC requirements for the CC-CMF system showed a lower bound of values for seismic force modification factors, and the system conservatively met the life safety objectives presented in the NBC. Additionally, different scenarios were contemplated for identifying ductility-related seismic force modification factor from pushover curves. The influence of height and gravity load levels on seismic force modification factors and the failure margin ratios were also studied by comparing the archetypes with different configurations.

Furthermore, Soureshjani and Massumi (2022) studied the seismic sequence of reinforced concrete (RC) moment-resisting structures with concrete shear walls. Two three-dimensional structures of short and medium height were premeditated and investigated under seven real mainshock–aftershock sequences of earthquakes. The models were encumbered and considered in accordance with the Iranian seismic code (4th ed.; Standard No. 2800) and the ACI-318. These structures were evaluated with the help of the nonlinear explicit finite element method. In this study, the maximum displacement, inter-story drift ratio, residual displacement, and ratio of aftershock PGA to mainshock PGA were analyzed. Due to the high imaginative stiffness of the shear walls along with their entirely elastic behavior, the aftershocks did not result in an intensification of the inter-story drift ratio or the relative displacement in the short structure model. The medium height model under the seismic sequences presented a significant growth in the relative displacement (approx. 25% in some cases), inter-story drift ratio, plastic strain, and residual displacement (42.22% growth on average) compared to the structure that was only subjected to the mainshock. In some of the cases, significantly, the aftershock doubled the residual displacement.

Xin et al. (2019) proposed that long-span bridges which are near the fault regions can sustain significant damage as a result of the special characteristics of earthquakes there, such as fling-step and forward-directivity effects. Using fling-step motions, the vibration behavior of a long-span concrete-filled steel tubular arch bridge was investigated in this paper. In order to construct a finite element model of the bridge, nonlinearities in the material and geometric nonlinearities were taken into account. Secondly, three types of dynamic loadings were presented in detail, incorporating recorded ground motions, residual components, and overemphasized pulse models. Afterwards, comparative and parametric analyses were performed to gain a deeper understanding of how components in fling-step motions affected seismic response. Based on the strain index used in the performance evaluation, the CFST arch might be dangerous at certain locations. Based on the findings of these studies, fling-step motions that consist of both static and dynamic pulses can have a significant impact on seismic response. Along with the pulse period, pulse amplitude, and mode contribution, the earthquake demands are affected by 'narrow band' effects at different pulse periods. In addition, Rutenberg and De Stefano [28] discussed the evolution of the seismic provisions for asymmetric structures, primarily within the context of the design eccentricity specified in the code. Although the Ed formulas were initially developed for linear ranges, the UBC formula leads to similar levels of ductility demand as predicted for similar yet symmetric structures. This is when overstrength is judiciously distributed. There are mainly single-story models studied in these studies. Recently, however, it has been suggested that single-story model results may be applicable to regular asymmetric shear buildings, albeit with minor modifications. In order to test the predictive power of pushover analyses, a 7-storey R/C wall frame is compared with the results of pushover analyses with mass locations based on the ED formulas.

3. METHODS

In this study, the effect of soil-structure interaction on the seismic response of concrete moment frames, including shear walls was examined according to the Iranian national building codes (Standard No. 2800) and the third type soil (medium density soils) were analyzed against the soil of structure foundation. In the present study, the effects of soil-structure interactions were studied in terms of the frictional contact model. The floor to floor height of these structures is 3.2 m and these models are made of reinforced concrete frames, together with intermediate moment frame systems and shear walls. First, the analysis and design of the buildings based on the ACI-318 design code under the effect of the seismic load have been done based on the Iranian standard 2800 (Standard No. 2800). The frame spans 5 m and the roof system is double-sided. In order to compare the results of the design of concrete buildings in terms of the Iranian national building codes (Standard No. 2800), three sets of reinforced frame-wall models were prepared. It is necessary to explain the ETABS.V.9.5 software used for modeling, analysing, and designing the 3D buildings, they were designed in accordance with the Iranian national building codes (Standard No. 2800). The foundation structure is also designed in SAFE.V.8.0 and the modeling was assisted by Abaqus.

4. RESULTS AND DISCUSSION

Types of seismic duration

In relation to determining the duration of intense movements, there are different methods using the characteristics and effective parameters of the earthquake acceleration-time curve. The methods that define the duration of strong movements using the acceleration characteristics of recorded earthquake maps can be divided into three categories as follows.

Interval duration

The simplest definition of duration time is interval duration time 1, in which the time interval between the first and the last time that the acceleration of the ground movements exceeds a certain value is considered as the duration of the earthquake. In this regard, Page considered the duration of the earthquake based on the threshold acceleration g of 0.05. In this definition, the shape of the record in the part of strong movements is not taken into account at all, and two completely different earthquakes with the same threshold acceleration may show the same duration.

Uniform duration

Another definition that takes into account the general characteristics of the record is called uniform duration. This duration is the sum of the time intervals when the acceleration exceeds a certain value. Bolt proposed this definition with two threshold values of 0.05 and g 0.10.

Significant durability

The basis of the third category of definitions is the cumulative distribution of earthquake energy, which is determined using acceleration mapping. This definition is called meaningful duration 2. The significant time period is calculated based on the square integral of the earth's acceleration. In most of these definitions, the intensity of Arias is used, which is the intensity of Arias in the form of relation 1:

1) IA = 2πg ∫0T a t dt2( )

In this regard, (a(t) is the acceleration at time t, which is determined by the map acceleration record, and IA indicates the amount of energy applied to the structure. The diagram of the changes in the intensity of Arias in terms of time is called Heuside diagram and picture 1 shows an example of it.

The Heuside diagram usually consists of a part with a low slope, which corresponds to the arrival of P waves. The middle part of the graph has a steep slope and is related to the main input energy due to S waves and surface waves. The slope of the end part of the graph is relatively low and is related to volume and surface waves that indirectly reach the accelerometer. The slope of each part of the Heuside diagram is actually the mean square of the acceleration.

The significant duration time is defined as a time interval that includes a certain percentage of the intensity of the arias. This percentage has been considered by different researchers in different ways. The most common definition is provided by Trifnak and Brady based on the time interval between 5% and 95% of Arias acceleration (Zhang et al., 2005).

In a research, the correlation of different parameters of earthquake durability with damage indicators on reinforced concrete structures has been investigated. Also, a large number of durability programs related to structural engineering to evaluate seismic improvement can be found in the articles. Hausner was one of the first researchers who suggested that structures should be designed in such a way that they have sufficient energy absorption capacity to resist the energies exerted by the movement of the earth. The energy demand of earth motion is also a function of the generated energy more than the input energy, all the input energy is the intensity and duration of the earthquake. Hausner also proposed to the structure during the time of earth movement, by damping and that in two earth movements with the same intensity spectrum, if the duration of one cycle of operation hysteresis is lost. This behavioral cycle of movement is more than the other, the two movements may have inelastic effects causing minor damage to the structure and cumulative damage effects are different. It should be added that the maximum acceleration of PGA is similar, while the duration of their resistance and hardness is different according to the conditions of the structure. In several studies investigating the degradation behavior, Ang and Bertro have conducted a wide research on the energy demand of hysteresis cycles in the nonlinear static analysis of structures under earthquakes. These studies show that reinforced concrete structures with different ductility have been examined, the energy demand from ground motion is dissipated by the structure in the form of damping and reversible elastic strain. Relationships between the energy of understanding the effect of ground motion duration on cumulative damage and the input mechanism and peak spectral velocity with the duration of strong ground motion associated with our failure is a step to prevent collapse caused by earthquakes in the future. This result will be closer to the ominous findings of Rahnama and Manuel, and it can help in improving regulations that indicate the existence of a relationship between input and construction energy demand (Papiani, 2010). Cyclic energy is the energy lost by the wheel behavior of reinforced concrete structures against multiple earthquake excitations, which are related to the irreparable plastic deformation of the structure, are very vulnerable. Researchers are mainly focus on the vulnerability of the duration of earth movement (Mujtahedi and Safari, 2017). In general, strong concrete refers to concrete that has more efficiency for the intended application than ordinary concrete.

For example, concrete that provides better reliability and durability against different service conditions, concrete that has excellent properties at early ages, or concrete that has more resistance properties than ordinary concrete, are examples of strong concrete. The properties that strong concretes may have include high initial strength, high final strength, high modulus of elasticity, long durability, high performance, more pumpability, high ability to pour in hot and cold weather, and... Usually more than one of the above properties is required for a specific application. For example, in skyscrapers, high ultimate strength, high modulus of elasticity, high pumpability and the ability to pour concrete without compaction are required. These concretes may contain materials such as fly ash, sintering furnace slag that is completely finely ground (silica fume, fibers, chemical additives and various other materials), alone or mixed with each other.
Today, engineers are increasingly using strong concrete in various applications, including major road construction works, construction of new highways, repair of existing roads, as well as the construction of tall structures, etc., because higher strength provides more design options. The improved properties of concrete in the early ages facilitate construction and renovation works, improve the quality and higher durability, increase the service period, and lead to a reduction in the cost of the structure during its useful life.

Characteristics of high strength concrete

In concrete with high strength, the ratio of water to cement c/w should be reduced as much as possible. Today, even a c/w = 0.18 ratio is used, in which case, some non-hydrated cement grains increase the density as fine grain fillers and, as a result, increase the strength. Obviously, in order to ensure the efficiency of such mixtures with very little water, it is necessary to use lubricants, super-lubricants and spreaders of fine particles in concrete. To increase the softness of such concretes (it increases with the increase of brittleness and brittleness of concrete) short fibers can be added to them. In the construction of such concretes (strength equal to steel and higher), hardening methods under pressure and temperature are used to process the concrete and provide high initial strength. In cases of execution, careful monitoring of the correct execution of concrete should be carried out using skilled personnel and appropriate equipment. Concrete processing should be done continuously and with sufficient humidity and at a temperature of 20 to 25 degrees Celsius (Maeini, 2015).

One of the most important things regarding the use of high-strength concrete in structures is careful attention to the mixing plan, its implementation and processing. Regarding the mixing plan, it should be mentioned that due to the multitude of parameters affecting the properties of high-strength concretes, a specific mixing plan method has not been proposed in valid regulations for this type of concrete. Therefore, in the practical applications of this type of concrete, it is necessary to determine the appropriate mixing plan with laboratory studies and trial and error method or any other valid method.

Another issue about high-strength concrete is that sometimes the consumption of cement in them is very high and may reach more than 500 kg/m3. This issue, in addition to increasing the cost of concrete, causes cracks in it due to overheating and shrinkage. Due to the presence of many cracks, such concrete cannot have an acceptable durability in harsh and corrosive environmental conditions. As stated, in order to increase the durability of these concretes, while reducing the ratio of water to cement and using super-lubricants, the amount of cement used has been reduced and instead of that, materials such as silica fume, fly ash, and iron furnace slag .. are replaced by fine grain materials.

The importance and benefits of using high strength concrete

The application and use of high-strength concrete instead of ordinary concrete has many technical-economic benefits, the most important of which can be mentioned as follows:

Increasing the stiffness and strength of the structure, which can reduce unwanted horizontal displacements, optimizing the useful space by reducing the geometric dimensions of the components, increasing the execution speed by simultaneously reducing the volume of operations and shortening the molding time, reducing the change in the axial length of the compression members that are used in High-rise structures are of particular importance.

Improving the mechanical properties, reliability, sealing and reducing the permeability of concrete against the penetration of harmful chemical or atmospheric factors, high elasticity modulus, high efficiency and high pumpability (Moeini, 2015). By examining high-strength concrete from the economic aspect, it should be noted that the use of super-lubricating additives and additional cement compounds such as fly ash, micro-silica, and slag of the forging furnace in the high-strength concrete mix, as well as increasing the quality of stone materials and applying control The extreme quality during the construction, transportation and handling of concrete and careful supervision during the concreting and processing stage are all among the factors that have an impact on the final price of high-strength concrete and cause an increase in the final price of this type of concrete. However, in most applications of high strength concrete, the benefits and merits of its use are so great that the increase in costs is compensated.

5. CONCLUSION

According to the study of Azizi et al. (2018) regarding the amount of drift in structures, we can conclude:In frames with different concrete strength, if the same dimensions are considered, the amount of drift in both frames is almost the same. The same drift is due to the same sections in the structures. In frames where the sections are designed for concrete with specific strength, despite the difference in the amount of resistance in the structure, it can be concluded that with the increase in strength, the dimensions of the sections will decrease and with the reduction of the sections, the amount of drift will increase. Therefore, the amount of drift in the structure with a strength of 50 Mpa has increased by about 10% compared to the amount of drift in the structure with a strength of 25 Mpa. Regarding the cover curves, it can be concluded that in the structure with different concrete strength and the same dimensions, with the increase in concrete strength, the strength of the whole structure has increased, and this increase in strength is due to the reduction of damage in the structure. Therefore, the amount of energy absorption in the frame with a strength of 50 Mpa is higher than the amount of energy absorption in the frame with a strength of 25 Mpa, which reduces the stiffness in the structure. Also, in the case that the structure is designed for high-strength concrete, due to the smaller dimensions of the sections compared to the structure with 25 MPa strength concrete, the non-linear resistance of the structure is reduced. But on the other hand, the ability to digest energy increases. As a result, the amount of energy absorption is reduced compared to the concrete structure with a strength of 50 Mpa. Regarding the ductility of the structures, it can be concluded that with the increase of concrete strength in the structures, when the dimensions remain constant, the ductility of the structures increases. But in the case that the structure is designed for concrete with high strength, the cross-section dimensions will be reduced. By reducing the overall cross-sectional dimensions, the strength of the structure will be imposed on the concrete and the behavior of the concrete will become more brittle. As a result, the role of steel will be reduced and finally the ductility of the structure will be reduced.

According to Mojtahedi and Safari's study (2017), three 3-, 9- and 51-story concrete buildings were modeled by Seismostruct 2016 finite element software and are affected by records that are scaled in terms of energy and have the same soil conditions. These records are different in terms of the effective duration so that the difference in the behavior of the structure can be checked in different durations. The results of the nonlinear analysis of the time history on the structure with the mentioned records show that the number of plastic joints created and the maximum displacement in earthquakes with high durability are far more than in earthquakes with low durability. Also, the study of the behavior of buildings during earthquakes with different durability shows that earthquakes cannot be sorted based on their apparent durability. Rather, the more the number of earthquake cycles that have an acceleration range greater than a certain limit, the greater its effects on the structure.

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