Optimization of High Strength Fiber Reinforced Concrete with Durability Characteristics for Seismic Applications

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SUMMARY:
High strength concrete exhibits several desirable mechanical properties, but its structural application in high seismic regions has been limited because of its brittleness and durability performance. The use of steel fibers in concrete can mitigate early cracking and improve ductile behavior. This research optimizes the parameters that affect the seismic performance and durability characteristics of high strength fiber reinforced concrete. Plain and fiber reinforced concrete specimens with high compressive strength were tested to obtain compressive and tensile strengths, modulus of elasticity, drying shrinkage, and permeability. In addition, nonlinear static analyses were performed on reinforced concrete frames to assess the benefits of high strength materials on the system's performance. The results indicate that high strength fiber reinforced concrete can achieve desired levels of ductility and durability for seismic applications. Nevertheless, the numerical results on reinforced concrete frames show that after certain strength limits, the improvement on the structure's performance is marginal and only leads to potential durability problems.

Keywords: Ductility, drying shrinkage, durability, concrete strength, pushover

1. INTRODUCTION

High strength concrete (HSC) is characterized by a high amount of cement and pozzolanic materials (e.g., silica fume), lower water-to-cementitious materials (w/cm) ratio, and smaller sized coarse aggregates. These characteristics increase the strength and impermeability of the concrete matrix, but also its brittleness and shrinkage strain. The structural performance of HSC components has been evaluated in the past, but the optimization of high performance concrete mixtures to achieve adequate seismic performance and durability characteristics has not been given enough emphasis. This study addresses the design of high strength fiber reinforced concrete (HSFRC) and HSC mixtures to provide adequate ductility and durability characteristics. In addition, an 8-story reinforced concrete (RC) moment resisting frame building is analyzed to obtain the concrete and steel rebar characteristics that optimize seismic performance and durability.

1.1. HSC ductile behavior

HSC is not commonly used in high seismic hazard zones because it exhibits a steeper descending stress–strain curve in compression than normal strength concrete (NSC), as shown in Fig. 1, which may lead to brittle failure mode (Palmquist and Jansen, 2001). The performance of HSC largely improves when steel reinforcement is added, but crushing concrete failure is still very abrupt (Kaminska, 2002). Experimental tests have shown early spallation (i.e., loss of cover concrete) in HSC columns before reaching the axial capacity calculated by ACI equations (ACI-ASCE, 1996; Paultre and Mitchell, 2003; Saatcioglu and Razvi, 1992). Early spallation is caused by low permeability of HSC that leads to drying shrinkage strain in the cover concrete, and a closely spaced reinforcement cage.

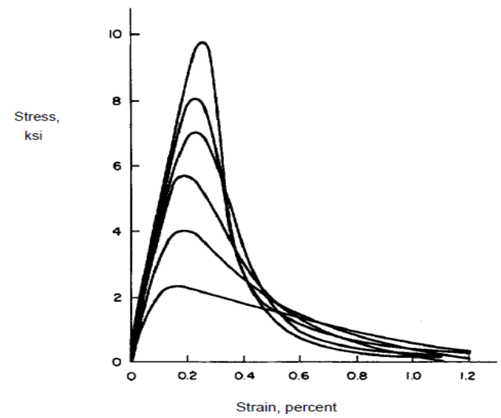

Figure 1. Stress-strain curves for concrete mixes of different compressive strength (Palmquist and Jansen, 2001)

1.2. Effect of steel fibers on HSC ductility and durability

The ductile properties of HSC components can be enhanced by using adequate transverse reinforcement, but early spallation and abrupt concrete crushing failure are difficult to prevent. Addition of fibers to the concrete mix increases the energy absorbing capability, ductility, and toughness of plain concrete (Fanella and Naaman, 1985; ACI, 1996). The randomly oriented fibers not only arrest cracking and its propagation, but also reduce spallation, which is an important consideration for HSC performance.

1.3. Durability of HSC and HSFRC

The seismic performance of RC structures is affected by aging of concrete, which is affected by the concrete's strength, permeability, and cracking resistance (Shah and Wang, 1997). In the case of HSC, its large compressive strength minimizes surface wear problems, such as abrasion and erosion (Liu, 1981). The permeability of HSC is lower because the concrete is denser and the mineral admixtures (e.g., silica fume) significantly reduce chloride penetration. However, HSC exposed to aggressive environmental conditions tends to crack easily due to low creep and high shrinkage characteristics controlled by the high cementitious content. Once the water-tightness is lost, the concrete starts to deteriorate due to different causes. Therefore, cracking is the main source of concrete deterioration in HSC, which leads to corrosion of steel reinforcing bars. Fibers should increase concrete's durability because they arrest cracking. Moreover, smaller crack widths in fiber reinforced concrete (FRC) impede chloride ions from contacting the steel rebars (Sahmaran et. al., 2008), hindering the development of expansive corrosion products.

Concrete is almost always specified based solely on its compressive strength, but usually failures of concrete structures are due to durability issues. Cracking reduces durability of concrete significantly, but in many cases, cracks have a negligible effect on the concrete compressive strength, and hence, compressive tests will not detect a durability problem.

2. SIGNIFICANCE OF THE RESEARCH

HSC for seismic applications needs to meet stringent strength, ductility, and durability requirements. The study evaluates the characteristics of HSC and HSFRC mixtures that minimize shrinkage strain, enhance deformation capacity, and arrest cracking. Thereafter, nonlinear static analyses are performed on mid-rise RC frames to optimize the use of concrete mixtures based not only on their seismic performance, but also their durability requirements.

3. EXPERIMENTAL PROGRAM

Six concrete mixtures were prepared to evaluate the factors affecting strength and durability characteristics of HSC. A control mixture of NSC with a design f_c' of 4 ksi was created. For the second mixture, steel fibers were added to the NSC mixture to create FRC. Hooked steel fibers were used to increase the pullout resistance (Yakoub 2011). The third mixture was the baseline case, a HSC mixture with a design f_c' of 12 ksi. A similar case that included fibers in the HSC mixture to obtain HSFRC was also prepared. The last two cases corresponded to HSC and HSFRC mixtures that included shrinkage reducing admixture (SRA) to reduce early cracking associated with shrinkage. Trial tests were conducted to evaluate the plastic behavior of some of the typical mixtures and measure their compressive strength development. Compressive and tensile strength, drying shrinkage, and permeability tests were performed on these specimens. Drying shrinkage tests were carried out to investigate the effect of steel fibers and SRA on shrinkage strains. Rapid chloride permeability test (RCPT) was also performed to evaluate the concretes' ability to perform under aggressive environmental conditions.

Table 1 shows the final mix proportions for the six different types of concrete mixtures prepared for testing. Nine cylindrical specimens of 4 in. diameter and 8 in. height were prepared for the first four cases, and three cylinders for the last two sets of mixtures with SRA. In addition, three 3 in. square and 10 in. long prismatic specimens for measuring drying shrinkage were prepared for the HSC mixtures. The following subsections detail the criteria used to achieve these mixes.

Table 1. Concrete mix proportions

Mixture properties	Concrete Mixture Cases					
	NSC	FRC	HSC	HSFRC	HSC + SRA	HSFRC + SRA
Target f_c' at 28 days (ksi)	4	4	12	12	12	12
w/cm ratio	0.45	0.45	0.30	0.30	0.28	0.28
Type II Portland cement (lb/yd^3)	500	500	790.5	790.5	790.5	790.5
Silica fume (7% of cm) (lb/yd^3)	-	-	59.5	59.5	59.5	59.5
Sand (lb/yd^3)	1200	1200	1200	1200	1200	1200
½ in. coarse aggregate (lb/yd^3)	1700	1655	1800	1755	1800	1755
Steel fibers (1% by vol.) (lb/yd^3)	-	132.5	-	132.5	-	132.5
Water (lb/yd^3)	225	225	255.0	255.0	238.0	238.0
SRA (gal/yd^3)	-	-	-	-	1	1
HRWRA (gal/yd^3)	4	5	3.7	4.1	3.5	2.9

3.1. Cementitious materials content and w/cm ratio

The use of high amount of cementitious materials and low w/cm ratio increases the concrete compressive strength, but not necessarily its long term durability. Low w/cm ratio and highly reactive pozzolanic materials (e.g., silica fume) improve the pore refinement reducing permeability, but they also increase shrinkage, brittleness, and cracking in the concrete (Mehta and Monteiro, 2006). Concrete with a high cementitious material content (more than 1000 lb/yd^3) can exhibit excessive thermal and drying shrinkage. Thus, the evaluated HSC specimens were designed to achieve the target compressive strength (i.e., $f_c' =$ 12 ksi at 28 days) with the minimum amount of cementitious materials. Silica fume was added to the mixtures because it increases the strength and reduces permeability. It also decreases the risk of thermal cracking by reducing the total cementitious materials content.

Because of the low w/cm ratio, HSC can also exhibit a substantial increase in autogenous shrinkage, especially during the first 24 hours after casting. Autogenous shrinkage occurs as a result of self-desiccation in low w/cm mixtures where sufficient water is not provided to complete the reaction with the cement (Shah and Weiss, 2000). Therefore, very low w/cm ratios should be avoided, even if superplasticizers improve concrete's workability, to prevent autogenous shrinkage. Also note that silica fume content has to be controlled because high amounts of this pozzolanic material result in higher autogenous shrinkage as shown in Fig. 2 (Brooks et. al., 1998).

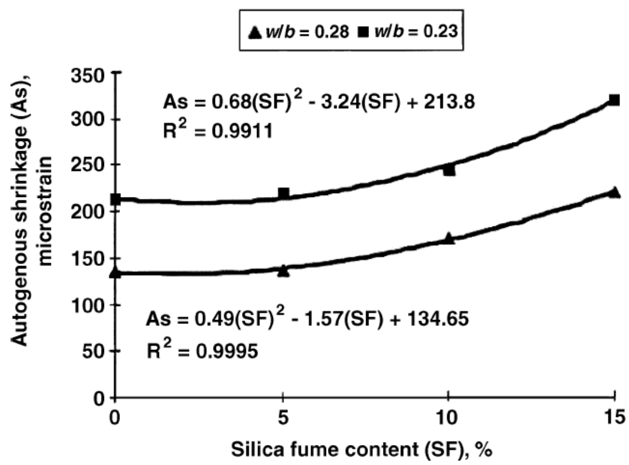

Figure 2. Autogenous shrinkage for different silica fume content and w/cm ratios (Brooks et. al, 1998)

To address the above constraints, the HSC mixtures of this study included 790 lb/yd^3 of Portland cement, and 60 lb/yd^3 of silica fume. The total cementitious material was lower than 1000 lb/yd^3 and the percentage of silica fume was 7%, which should not lead to a significant increase in autogenous shrinkage. The w/cm ratio was about 0.30, which also prevents large autogenous shrinkage, and at the same time, is sufficiently low to allow the development of the required compressive strength of 12 ksi.

3.2. Coarse and fine aggregates

Concrete compressive strength can be increased by using small size coarse aggregates because their greater surface area increases the strength of the interfacial transition zone. Aggregate characteristics are also very important to prevent shrinkage, which leads to early cracking. In fact, aggregate content in HSC is the most important factor affecting the concrete's drying shrinkage and creep. The amount of coarse aggregate should be as high as possible because drying shrinkage in aggregates is negligible compared to that in the cement paste as shown in Fig. 3.

Unlike the desirability of smaller aggregate size to reach high compressive strength, a large coarse aggregate helps prevent drying shrinkage. Thus, these two aspects have to be balanced during the concrete mix design. To keep the drying shrinkage and creep low, the cement paste-aggregate volume ratio was maintained close to 35:65 and the fine-coarse aggregate volume ratio was kept close to 2:3 (Mehta and Monteiro, 2006). Also, limestone coarse aggregate with a maximum size of ½ in. was used to prevent drying shrinkage. Limestone was selected because hard and strong aggregate types with high modulus of elasticity and low coefficient of thermal expansion are better for producing very high-strength concrete mixtures (Aitcin and Mehta, 1990).

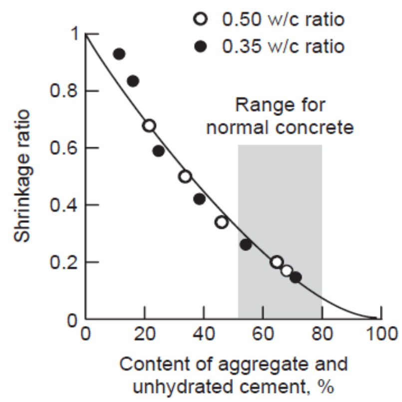

Figure 3. Effect of aggregate content on shrinkage ratio (ACI, 1971)

3.3. Steel fibers

Experimental tests have demonstrated that fibers reduce spallation, which is a common phenomenon in HSC components. Steel fibers also provide additional internal confinement in reinforced concrete elements improving their response especially under cyclic loading (Trono et. al., 2012). Although a small volume fraction of steel fibers is generally used in concrete, the fibers have high surface area and therefore require large amount of cement paste. The amount of steel fibers in concrete is commonly limited to about 2% by volume because of a reduction in workability, and difficulty to ensure uniform dispersion.

ACI (1996) indicates that a lower volume fraction of fibers (up to 1%) reduces shrinkage cracking, whereas a moderate volume fraction dosage (1% to 2%) increases the modulus of rupture, fracture toughness, and impact resistance of the concrete. Fibers delays age-related degradation because they tend to arrest concrete cracks caused by shrinkage, thermal, and mechanical stresses. Some studies, however, have not found a reduction in drying shrinkage for FRC (Mehta and Monteiro, 2006). In addition, steel fibers are not subjected to corrosion as long as they are embedded in the concrete. The trial tests included 1.25% by volume of steel fibers, but the amount of fibers was reduced to 1% by volume in the final mixtures to increase workability and ensure a uniform dispersion. Low carbon hooked steel fibers of aspect ratio 60, diameter 0.022 in. and length 1.3 in., were used in the mixtures.

3.4. Admixtures

HSC and HSFRC mixtures were prepared using a typical dosage of Eclipse Floor 200 SRA of 1 gal/yd^3 to reduce the concretes' shrinkage. Using SRA reduces the compressive strength of concrete as the liquid admixture adds up to the mixing water. Thus, after conducting trial tests, the w/cm ratio was adjusted to balance the drop in compressive strength. In addition, Glenium 7710, a polycarboxylate based high range water reducing admixture was used to achieve the desired level of workability in all the concrete mixtures. Unlike other type of water reducers, this admixture does not delay the setting process and can be used when shrinkage tests are conducted, including initial length measurements after the first 24 hours.

4. EXPERIMENTAL RESULTS

4.1. Compressive strength

Standard compressive strength tests were conducted on three samples from each set after 28 days, according to ASTM C39 procedure. The results are shown in Table 2. The first unexpected result was that f_c' for the NSC mixture was twice the target strength. Also, the FRC samples (NSC with steel fibers) rendered a lower f_c' due to a significant reduction in the workability of the concrete mixture that resulted in larger compaction voids. The average f_c' for the HSC mixture was 13.5 ksi after 28 days. The addition of steel fibers to the mixture (i.e., HSFRC) slightly reduced the average f_c' , and increased the variability of measured strengths. This indicates that the level of dispersion and directional orientation of the fibers affect f_c' of concrete containing fibers. However, the addition of steel fibers led to an increase of the strain at peak strength of about 25 % (Fig. 4). Also, the average tensile strength increased approximately 45 % for the HSFRC samples with respect to the tensile strength of HSC. The compressive strength of specimens containing SRA was reduced. The decrease was significant in the mixture with fibers (HSFRC+SRA) because of the combined effect of the SRA and a reduction in workability due to the lower w/cm ratio and the presence of steel fibers.

Table 2. Compression test results

Identification	Average mass (lb)	Average f_c' (ksi)
NSC	8.667	8.263
FRC	8.609	6.953
HSC	8.896	13.515
HSFRC	9.034	13.063
HSC + SRA	9.014	11.442
HSFRC + SRA	8.461	7.106

4.2. Stress-strain curves and modulus of elasticity

Stress-strain curves for the NSC, HSC, HSFRC and HSC + SRA concrete samples were obtained by using three equidistant strain gages attached at the mid height of each specimen. Fig. 4 shows the stress-strain curves for the different cases, and the moduli of elasticity are summarized in Table 3. In this case, the HSFRC sample provided the highest strength and ultimate strain. It was observed that some of the steel fibers in the HSFRC sample had already yielded at the ultimate load, an indication of adequate bond formation between the fibers and the concrete.

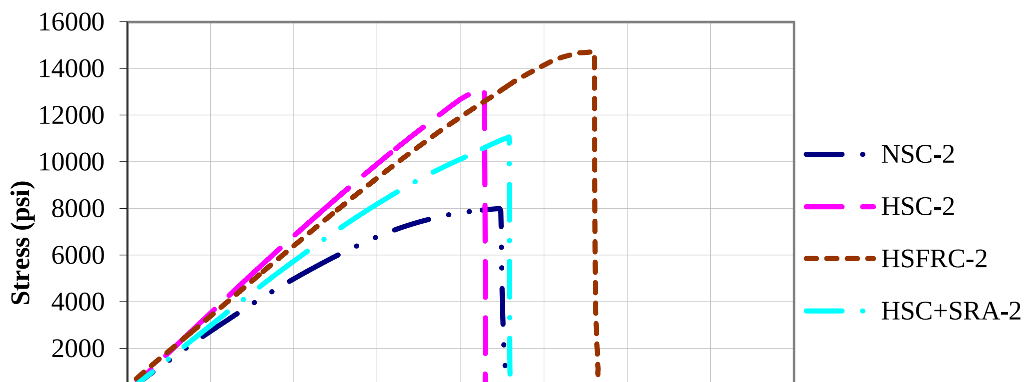

Figure 4. Stress-strain curves for selected specimens

The other important result from this test is that the modulus of elasticity of the HSFRC specimen is lower than that of the HSC, although the HSFRC specimen has higher ultimate strength. As shown in Fig. 1, the slope of the ascending portion of the stress-strain curve rises with increasing compressive strength. However, Fig. 4 indicates a different behavior for the HSFRC case, confirming the material can undergo significant elastic deformations while at the same time achieving higher ultimate strength.

Table 3. Computed moduli of elasticity

Identification	f_c' (ksi)	E (ksi)
NSC-2	7.999	5150
HSC-2	13.109	7050
HSFRC-2	14.737	6100
HSC + SRA-2	11.074	5700

4.3. Free drying shrinkage test

HSC mixtures usually exhibit large drying shrinkage. Free drying shrinkage tests were conducted to evaluate the effect of fibers and SRA on drying shrinkage. The tests were conducted as per ASTM C490 standard. The specimens were cast on 3 × 3 × 10 in. molds, and were demolded after 24 hours. The samples were wet cured for 7 days, and then kept under ambient conditions. The specimens' length was recorded at 1, 7, 14, 21, 28, and 91 days. As observed in Fig. 5, the HSFRC specimens exhibited lower drying shrinkage values compared to the HSC samples, indicating that steel fibers mitigate drying shrinkage. Samples that included SRA showed superior performance in terms of reducing long term drying shrinkage. In general, the relatively low drying shrinkage values validate the concrete mixture designs.

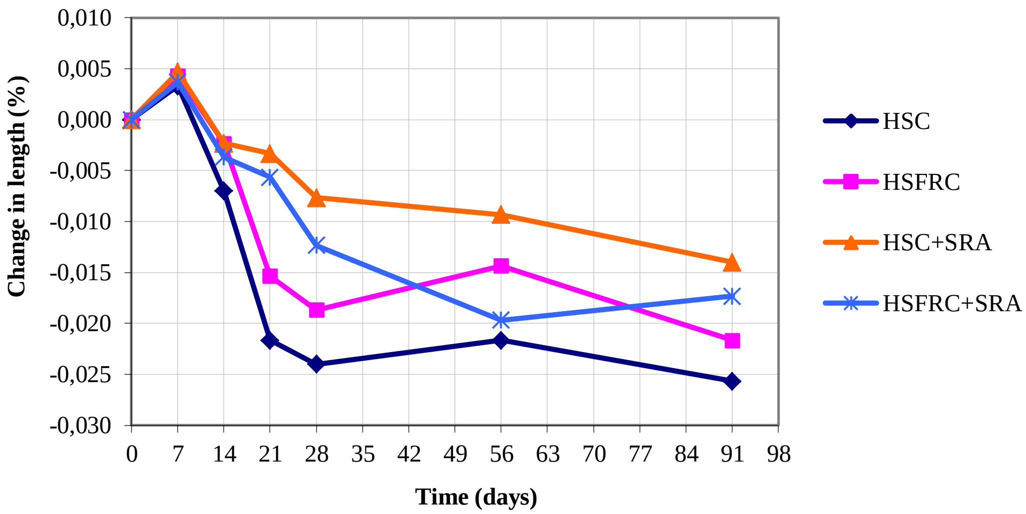

Figure 5. Drying shrinkage curves

4.4. Rapid chloride permeability test (RCPT)

The rapid chloride permeability test (RCPT) relates chloride penetrability of the concrete to its resistivity. The test records the number of coulombs that pass through a concrete specimen. According to ASTM C1202, a high chloride permeability rate corresponds to more than 4000 coulombs; a moderate rate ranges from 2,000 to 4,000 coulombs; a low rate from 1,000 to 2,000; and very low rates correspond to less than 1,000 coulombs. For the test, 2 in. thick concrete disks were cut from three different cylinders for each case, and preconditioned as per ASTM C1202. The average adjusted charge passed after a six-hour period is presented in Fig. 6 for individual tests. As observed, HSC has low chloride permeability rate, significantly lower than that of NSC. In the case of HSFRC, the current limit was exceeded in two of the three samples because of the fibers' conductivity. For the remaining HSFRC sample also, the steel fibers' conductivity artificially increased the charge. The RCPT results for this HSFRC test do not disqualify the concrete permeability, and it can only be concluded that the actual chloride permeability in the sample is lower than the measured value (Stanish et. al., 2000).

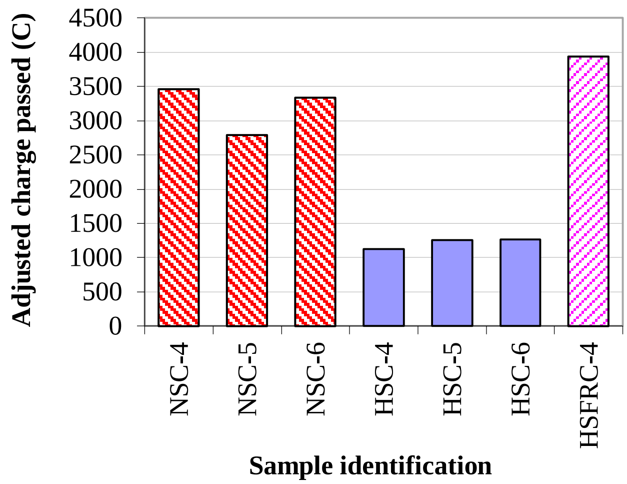

Figure 6. RCPT results (HSFRC-4 charge is affected by steel fibers' conductivity).

The RCPT results of NSC and HSC samples indicate a very low permeability in an uncracked condition, although it may increase by the introduction of cracks (Wang et al., 1997). It is expected that the permeability of FRC and HSFRC will be even lower than that of equivalent cases with no steel fibers, but it could not be measured using RCPT. Fiber reinforcement reduces the permeability of cracked concrete because it imparts crack growth resistance, and increases surface roughness of individual cracks. The finer the crack, the less likely it is to contribute to durability problems. Crack widths of less than 0.10 mm are insignificant. Because permeability is related to the cube of the crack width, several smaller cracks will be less permeable than one large crack.

5. NUMERICAL SIMULATION

HSC can reduce the ductility and durability characteristics of concrete. The potential for cracking, for instance, can be significantly increased by using HSC. However, the above experimental results and available data indicate that it is possible to achieve compressive strengths of 10-12 ksi, and still have adequate ductility and durability characteristics. Thus, a nonlinear static (pushover) analysis of a moment resisting frame was performed to evaluate the effect of high strength materials on the structure's seismic performance, as well as the pros and cons of increasing the compressive strength. The selected 8-story frame has three bays with 20 ft spacing, a first story height of 15 ft, and 13 ft high stories after that. The frame was designed for a Californian site (Haselton and Deirlein, 2007) using NSC. For the original design, the exterior and interior base columns supported an axial load equivalent to $0.17f_c'A_g$, and $0.31f_c'A_g$ respectively, where A_g is the columns' cross section. For this study, the RC mechanical properties were modified to evaluate the effect of HSC and HSFRC mixtures on the building's performance. The study included variations of f_c', yield strength of steel rebars (f_y), use of plain concrete or HSFRC with 1% volume of fibers, and variations in moment-rotation capacity of the plastic hinges. The HSC mechanical properties obtained from the experimental results were used in the numerical models. The resulting pushover curves are shown in Fig. 7.

Case 1 in Fig. 7, NSC-C6-fy60-PH0, includes the NSC from the original design in which C6 indicates the column compressive strength f_c' = 6 ksi, fy60 refers to rebars' yield strength f_y= 60 ksi, and PH0 corresponds to the base moment rotation diagram in the nonlinear range. In case 2, HSC-C13-fy60-PH0, f_c' was increased more than twice, but the building strength practically did not change. The advantage of increasing f_c' from 6 to 13 ksi, however, is that the rebar yield strength can also be increased. For instance, case 3, HSC-C13-fy100-PH0, is similar to case 2, but f_y was increased to 100 ksi. The use of high strength steel (HSS) almost doubles the building's shear capacity, although the ductility is reduced with respect to NSC. In case 4, HSFRC-C13-fy100-PH1, HSFRC is used to increase the system's ductility. Based on the above experimental results and literature review, the plastic rotation was increased by 25% and the moment capacity by 10% with respect to the base moment rotation diagram. The pushover curve for case 4 shows that the addition of fibers has a significant increase on the building's ductility.

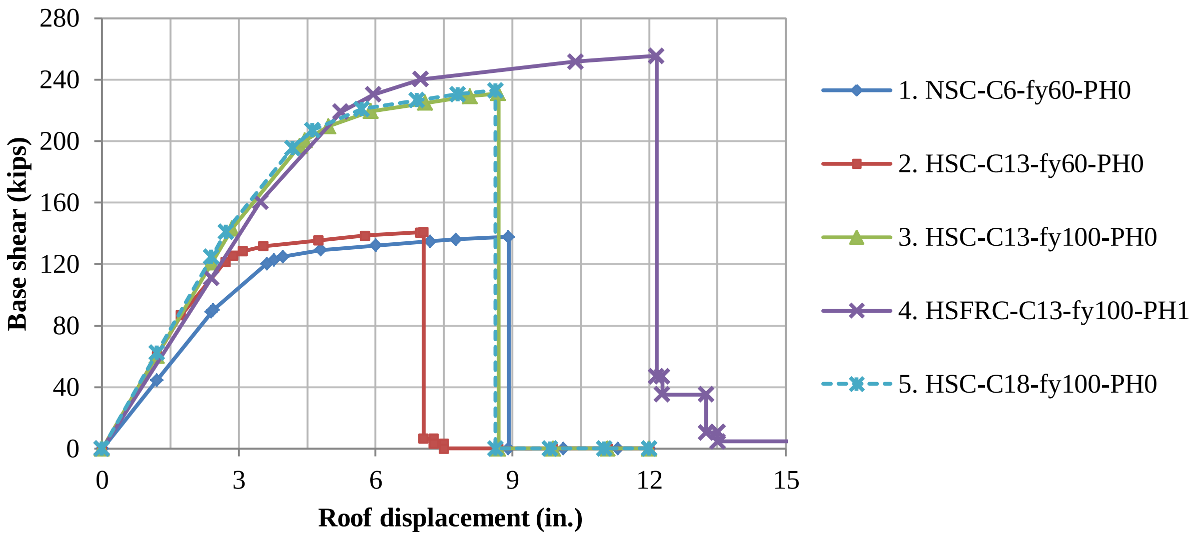

Figure 7. Pushover curves for the different analysis cases

Note that HSS is not commonly used with NSC because of the possibility of concrete crushing failure and reduced confinement due to the smaller amounts of required HSS. Thus, the main benefit of using HSC is the optimal utilization of HSS. Efficient use of HSS can be obtained for mixtures with f_c' of 10-12 ksi. A larger concrete strength will only lead to less ductile characteristics and durability problems. For instance, in case 5, HSC-C18-fy100-PH0, the concrete strength in the columns is f_c' = 18 ksi, but the corresponding pushover curve shows that the building's performance does not improve with respect to case 3, in which the concrete strength is f_c' = 13 ksi. On the other hand, a concrete with f_c' beyond 12-13 ksi will require higher amount of cement and pozzolanic materials, and lower w/cm ratio, leading to larger autogenous and drying shrinkage, higher brittleness, and vulnerability to early cracking.

6. CONCLUDING REMARKS

Experimental tests and numerical simulations were used to optimize the performance and durability of RC systems in high seismic hazard zones. Concrete cylinders for NSC, HSC, FRC and HSFRC were developed. In the case of HSC, the main factor causing durability problems is cracking. There are many constraints to the concrete mixture that need to be efficiently implemented to reduce HSC cracking. For instance, the mixtures for FRC and HSFRC+SRA used in the study did not properly work because, in an effort to reduce the cementitious material content that affects drying and thermal shrinkage, the mixtures did not have sufficient cement paste and workability. Similarly, the major factors contributing to brittle behavior of HSC are the small ultimate strain, high modulus of elasticity, and cracking propensity. These problems can be addressed by optimizing the mixture parameters. Also, the use of steel fibers in properly designed HSC mixtures reduces shrinkage, and increases the ultimate strain of concrete specimens. The study shows that it is possible to develop HSC mixtures for target f_c' values of 10-12 ksi with adequate ductility and durability characteristics by controlling the cement content, w/cm ratio, coarse aggregates, and pozzolanic materials (e.g., silica fume). However, the concrete needs to be carefully designed to prevent lack of workability and hydration, as well as eliminate compaction voids. Thus, for HSC, it is necessary to specify not only the concrete compressive strength, but also the maximum concrete permeability and especially shrinkage strain.

The numerical simulation showed that HSFRC can significantly increase the building's performance. The main benefit of using HSC is the possibility of using HSS, whereas steel fibers can enhance the internal confinement and ductile component characteristics. Concrete mixtures with f_c' of 10-12 ksi can be used for these purposes. Concrete mixtures with larger compressive strengths will only lead to less ductile characteristics and durability problems, without a significant improvement on the system's seismic performance.

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