16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2205

Registration Code: S-G1464116769

SEISMIC ANCHORAGE OF DRY STORAGE CASKS

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Abstract

Dry storage casks (DSCs) store spent nuclear fuel (SNF) rods from nuclear power plants (NPPs). DSCs are a temporary storage solution licensed for 20 years, although they may be relicensed for operation periods up to 60 years. DSCs are being re-evaluated as a potential mid-term storage solution, where operating periods may be extended to 300 years. The potential extension of DSC compliance period increases the seismic hazard, resulting in very large horizontal accelerations and destabilizing effects from vertical accelerations. DSCs are typically unanchored, but units located in moderate to high seismic regions may slide and/or tip over, damaging the cask internals. This research focuses on the benefits of seismic anchorage of DCSs.

Two types of anchorage are investigated: (a) conventional bolt details with steel chairs using designs adopted from anchoring liquid storage tanks, and (b) stretch length bolt details with steel chairs, which performed very well during the 2010 Maule, Chile earthquake. In the first phase of the study, single anchor tests are performed using both conventional and stretch length bolts under dual actuator cyclic tension and shear. The evaluated stretch lengths are equivalent to four, six and eight bar diameters. Two thicknesses are also considered for the plates of the steel chair: (i) 12.7 mm and (ii) 6.35 mm. The 6.35 mm steel plates are used to investigate the effects of allowing the steel chair to yield compared to a steel chair that remains elastic. In the second phase, a group of anchors using the steel ring to clamp the cask were tested on a 1:2.5 scaled DSC under quasi-static horizontal cyclic loads and additional tests were performed using a shake table.

The experimental results are presented and compared for conventional and stretch length bolt details, as well as the scaled DCS in terms of load, displacement, and hysteretic energy capacity. It is shown that stretch length bolt anchorage details provide superior seismic performance compared to conventional bolt anchorage details.

Keywords: Seismic Anchorage; Stretch Length; Combined Tension and Shear; Dry Storage Cask; Shake Table Experiment

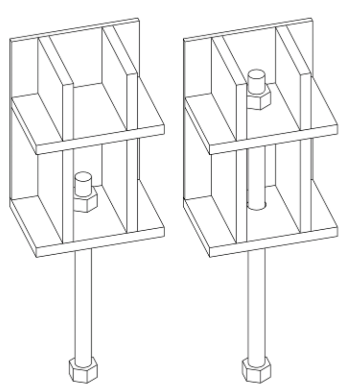
1. Introduction

For vertical containment structures that do not have significant ductility, a design that utilizes plastic yielding of anchor bolts connecting the structure to its foundation can be used to provide structural ductility to the system [1]. One type of vertical containment structure is a Dry Storage Cask (DSC), which is used to store spent nuclear fuel (SNF) rods from nuclear power plants. DSCs are considered a temporary storage solution for nuclear waste and are usually licensed for 20 years, although they may be relicensed for operation periods up to 60 years. However, DSCs are being re-evaluated as a potential mid-term storage solution, where operating periods may be extended up to 300 years. With the consideration of DSCs for storing SNF for hundreds of years the seismic hazard analysis results in very large horizontal accelerations and destabilizing effects from vertical accelerations due to the longer-term operating periods. DSCs are typically free standing structures that rest on a reinforced concrete pad. During a large seismic event a free standing DSC may tip over and/or experience excessive sliding leading to collisions with other casks or structural components, possibly causing damage to cask contents. By providing an anchorage system that behaves in a ductile manner, the threat of damaging the cask internals during a large seismic event due to tip over or excessive sliding can be avoided.

A steel ring designed to clamp the cask on a concrete pad is investigated as part of the anchorage system. Two different ring configurations are considered, a free steel ring and a welded steel ring; in both cases the steel ring is bolted to the concrete pad. In addition, two types of anchor bolts are investigated for the steel ring (Fig. 1): (i) conventional bolt details with steel chairs using designs adopted from anchoring liquid storage tanks, and (ii) stretch length bolt details with steel chairs. A stretch length bolt is an anchor bolt that has a length extending beyond the concrete surface in which it is anchored.

After the 2010 Maule earthquake in Chile, the SEI Industrial Assessment Team (IAT) observed that anchor fracture contributed to substantial foundation, connection, and structural damage [2]. The IAT also noted extensive evidence that base connections incorporating a stretch length did not experience anchor fracture, promoting good seismic performance of the attached structures. As a result of this report and empirical evidence from past-earthquake investigations, ACI 318-14 Chapter 17 adopted the requirement that for anchors to be regarded as a ductile steel element, a stretch length of at least eight bar diameters (8 db) is to be provided unless otherwise determined by analysis [3]. However, the eight bar diameter requirement is not based on experimental results; but rather it is based on observations of good performance in historical earthquakes as well as engineering judgment.

NEHRP [1] seismic provisions for new buildings and other structures suggests providing adequate stretch length in the yielding section of anchor bolts to accommodate the maximum inelastic displacements and rotations. However, this document does not recommend any specific length or analysis procedure to determine an adequate stretch length.



(a) (b)

Fig. 1 – Anchor bolt chairs: (a) conventional anchor bolt; (b) anchor bolt with stretch length

There is little research on the effects of providing a stretch length and what the appropriate length should be to enable a ductile response. Trautner (2014) investigated the effect of providing stretch length anchors at the column base of seismic force resisting systems [4]; based on four column baseplate experiments. The results showed that increasing the stretch length leads to an increase of the ultimate deformation capacity of the connection. However, due to the limited number of available experiments, the authors concluded that additional studies are required to understand the impact of stretch length and material ductility on baseplate and anchor bolt behavior.

The use of anchor bolts with a stretch length permits tensile yielding over a significant bolt length, increasing the tensile displacement capacity of the anchor and lateral displacement capacity of the system. Because code specified stretch lengths are not based on experimental results, this research evaluates the behavior of stretch length anchors with lengths of 4 db, 6 db, and 8db. To provide additional displacement ductility to the system, a steel chair designed to yield is also studied and compared to a steel chair that is designed to remain elastic, which is the typical design. To evaluate the effectiveness of providing a stretch length and/or a steel chair designed to yield, single anchor tests are performed under combined tension and shear loads. After evaluation of the single anchor tests, a group of anchors using the steel ring to clamp the cask were tested on a 1:2.5 scaled DSC under quasi-static horizontal cyclic loads and additional tests were performed using a shake table.

2. Single Anchor Tests

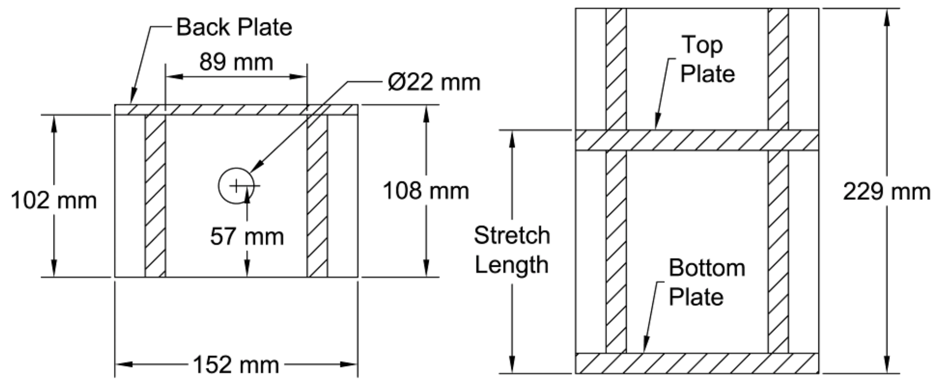
Single anchor tests were performed at the University of Utah to evaluate the effectiveness of providing a stretch length anchor and/or steel chair designed to yield. To emulate the demands an anchor bolt would experience in an actual structure combined tension and shear loading is used. The benefit of performing single anchor tests is that they allow a large number of tests to be performed examining different variables. In this research the variables examined are as follows:

1) Two steel chair thicknesses (yielding and elastic)
2) Conventional anchors and three different stretch length anchors (4 db, 6 db, and 8 db)

To ensure a ductile response of anchor bolts ACI 318-14 and ACI 349-13 [5] require that the bolts achieve a tensile test elongation of at least 14 percent, and a reduction of area of at least 30 percent. To satisfy these requirements ASTM F1554 Gr. 36 hex headed anchor bolts with a diameter of 19 mm are used. In this research, the mechanical properties of these anchor bolts were obtained from tension tests; they achieved a tensile elongation of 25% and a reduction of area of 71%. The 19 mm diameter anchor bolts were chosen to provide an appropriately scaled anchor for the 1:2.5 scaled DSC. These anchor bolts have a smooth shank with the threads positioned outside the concrete.

Once the size and type of anchor bolts was selected, the design of the steel chair was performed following a procedure specified by the American Petroleum Institute (API) standard 650 [6]. This allowable stress design procedure produced a steel chair design that remains elastic at the full tensile strength of the anchor bolt. The result of the design is shown in Fig. 2, which consists entirely of 12.7 mm steel plates with the exception of the 6.35 mm-thick back plate that would be in contact with the DSC. The top plate is moved vertically to accommodate different stretch lengths. To produce a steel chair that yields before the full tensile strength of the anchor is reached, a steel chair consisting of 6.35 mm steel plates was also built. The overall dimensions of the 6.35 mm thick chair are identical to those of the 12.7 mm chair shown in Fig. 2.

Sixteen combined tension and shear anchor tests were performed to evaluate six parameters: conventional bolts (0 db); stretch length bolts considering stretch lengths of 4 db, 6 db, and 8 db; as well as 6.35 mm and 12.7 mm steel chairs. The test matrix for the combined tension and shear anchor tests is shown in Table 1. A limited number of yielding chairs were tested due to the damage caused to the top plate for each experiment.



(a) (b)

Fig. 2 – Steel chair dimensions: (a) plan view; (b) front elevation

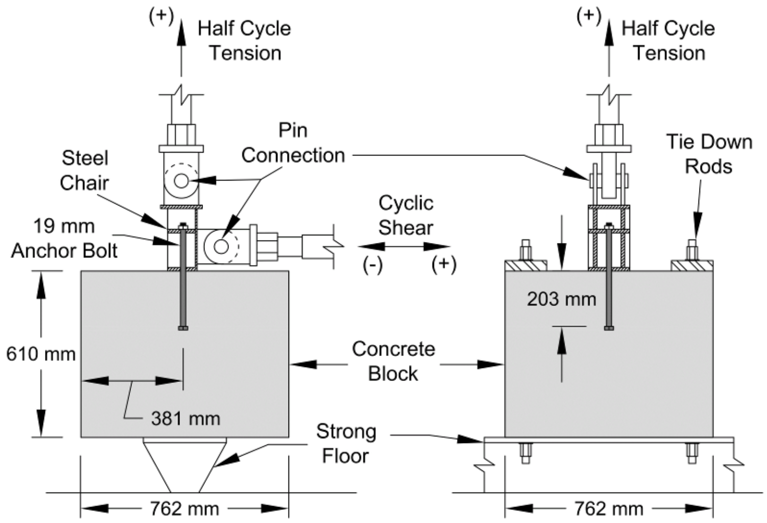
All tests are performed using two actuators, one in the vertical and one in the horizontal plane, as shown in Fig. 3, to simulate the shear and tension forces experienced by an extreme anchor bolt during the anchored cask test. The loading protocol of Fig. 4 is used, where the blue curve in Fig. 4(a) represents horizontal actuator displacement and the red curve in Fig. 4(b) represents vertical actuator displacement. The vertical actuator only acts in tension, whereas the horizontal actuator performs full cycles and has an amplitude equal to 1/2 of the vertical displacement. The tension and shear protocols are in phase and positive displacements correspond to a pull for both actuators.

Figure 5 shows the tension and shear hysteresis for a bolt with an 8 db stretch length and an elastic steel chair (12.7 mm thick). The tension hysteresis in Fig. 5(a) is representative of a bolt under tension with a distinct yield point followed by strain hardening. In the dual actuator tests, the ultimate tensile force achieved by the anchor bolt was less than that observed in monotonic tension tests of the bolt, shown as a dashed line in Fig. 5(a). This slight reduction in ultimate force can be accounted for by the introduction of shear forces and the cyclic nature of the experiment. Figure 5(b) shows the shear hysteresis, which shows an asymmetric response. For positive displacements, the measured shear force progressively increased for each displacement step up to a maximum shear value of 12.56 kN. However, for negative displacements a maximum shear value of 6.22 kN was measured. These shear values are relatively low when compared to the shear forces measured during the anchored cask experiment which was approximately 44.5 kN of shear per bolt. These lower shear values in the single anchor dual actuator tests are a result of the location of the horizontal actuator's connection to the steel chair.

Figure 6(a) summarizes the sixteen single anchor tests in terms of tensile displacement capacity. From Fig. 6(a) three trends are clear: (i) providing a stretch length leads to a significant increase in tensile displacement capacity; (ii) decreasing the stretch length from the code specified 8 db did not decrease the tensile displacement capacity of the anchor. This result is mainly contributed This result is mainly attributed to the concentration of stresses (shear and tension) at the concrete interface resulting in similar failure displacements regardless of the stretch length; (iii) providing a steel chair that yields increases the tensile displacement capacity for all cases. This increase is due to buckling of either the bottom plate for conventional anchors or the top plate for stretch length anchors as shown in Fig. 6(b). Plate buckling reduces the displacement demand on the anchor bolt and enables a greater displacement to be reached. However, buckling of the plates permanently damages the steel chair, making replacement of the chair necessary.

Table 1 – Single Anchor Test Matrix

Chair Thickness	6.35 mm Steel Chair				12.7 mm Steel Chair			
Stretch Length	0 db	4 db	6 db	8 db	0 db	4 db	6 db	8 db
Number of Tests	2	1	1	1	2	3	3	3



(a) (b)

Fig. 3 – Single Anchor Test Setup: (a) Side Elevation; (b) Front Elevation

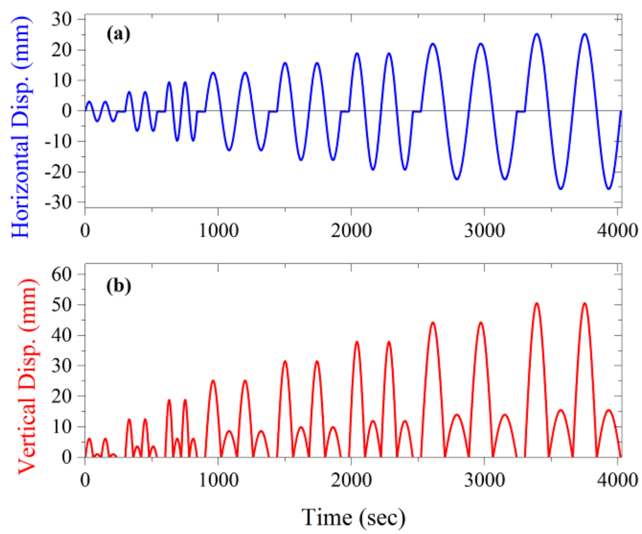
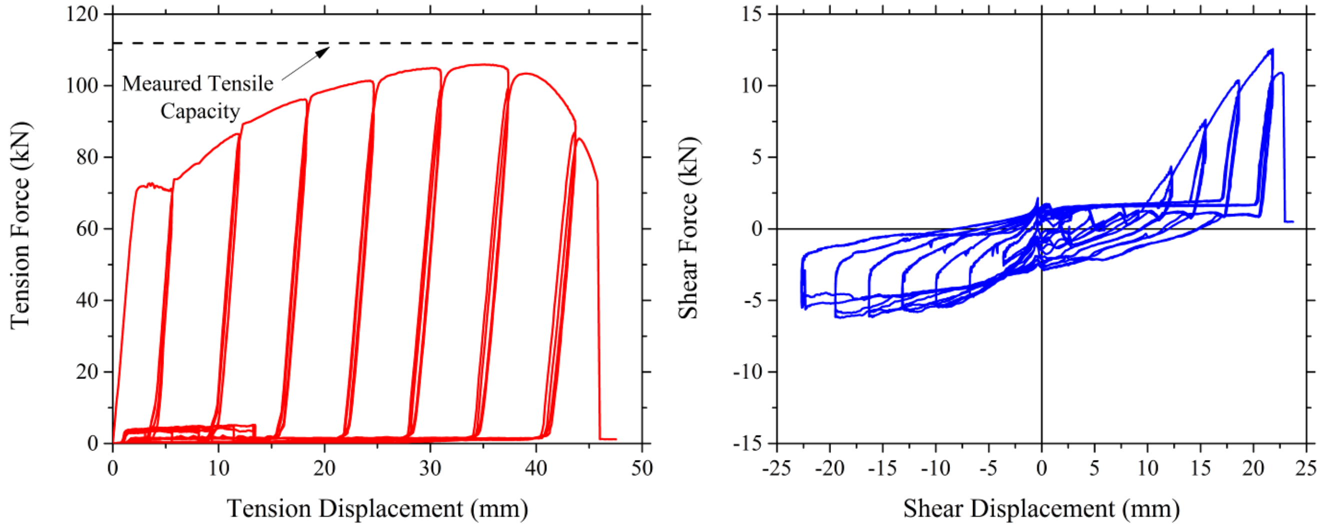


Fig. 4 – Dual Actuator Loading Protocol: (a) Horizontal actuator; (b) Vertical actuator

3. Anchored Dry Storage Cask

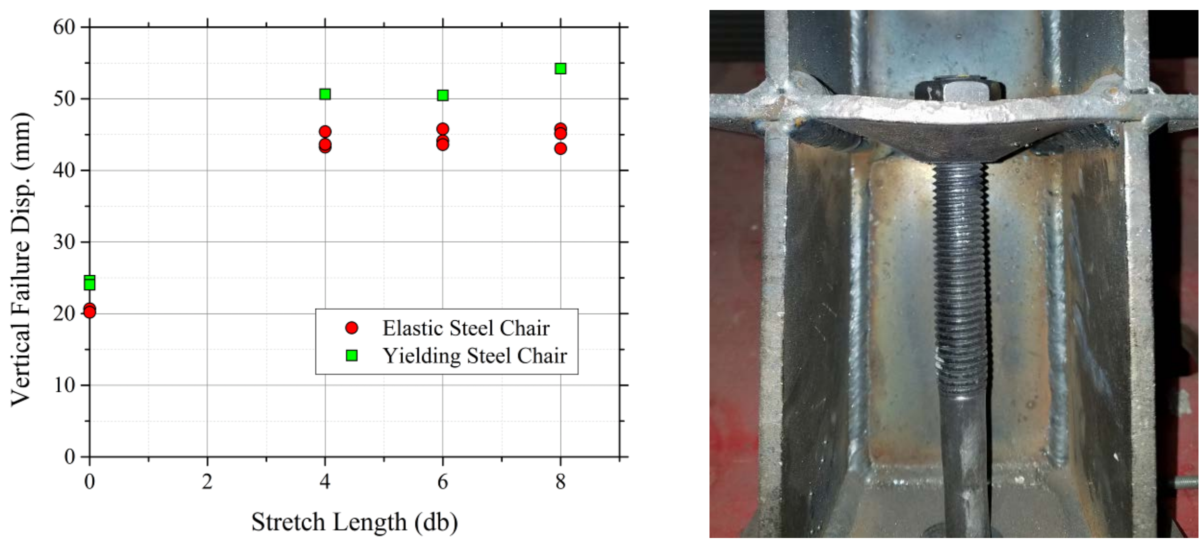
3.1 Quasi-Static Experiments

After evaluation of the single anchor tests, a group of stretch length anchors was tested at the University of Utah on a 1:2.5 scaled DSC under quasi-static horizontal cyclic loads applied at the centroidal height. A steel ring designed to clamp the cask to the concrete foundation was used as part of the anchoring system. For the anchored DSC two different steel ring configurations were considered, a free ring and a welded ring. The free ring configuration can be used to anchor existing free standing DSCs since the steel ring is not attached to the DSC. In this case, there is a small gap between the ring and DSC which was filled with non-shrink high strength grout. The welded ring configuration requires the steel ring to be welded to the DSC. Welding of a steel ring to existing DSCs is not permitted. Therefore, the second steel ring configuration can only be used for new construction. The performance of both steel ring configurations is evaluated in terms of load, displacement, and hysteretic energy capacity.



(a) (b)

Fig. 5 – 8 db Stretch Length with Elastic Steel Chair Response: (a) Tension; (b) Shear

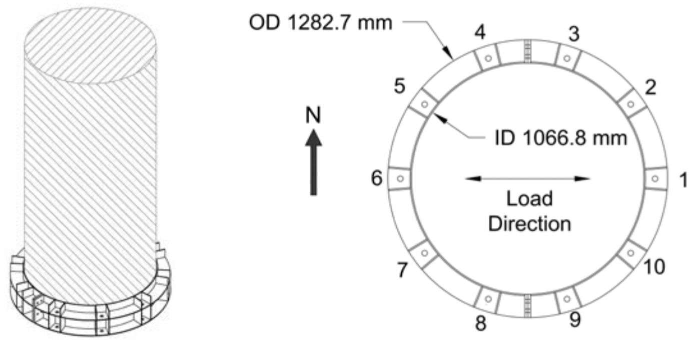


(a) (b)

Fig. 6 – Single Anchor Tests: (a) Single Anchor Failure Displacements; (b) Top Plate Bending [Yielding Chair]

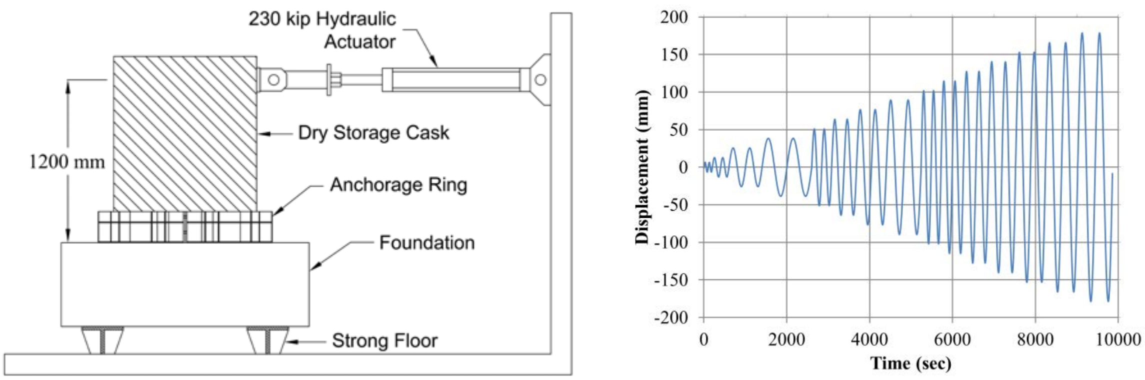
The single anchor tests showed that by combining a stretch length anchor with a length of 8 db and a steel chair intended to yield produces the most ductile anchorage system. Therefore, for the 1:2.5 scale DSC an anchorage system was developed, which consisted of a steel clamp ring made up of 6.35 mm steel plates and bolts with a 152 mm (8 db) stretch length.

To test the effectiveness of the ductile anchorage system for DSCs an anchored 1:2.5 scale DSC was tested under a quasi-static displacement loading protocol. The 1:2.5 scale DSC had a height of 2,400 mm and a diameter of 1,054 mm; the center of gravity of the DSC was 1,200 mm above the ground. The number of bolts was determined by following anchorage requirements from both ACI 318-14 and ACI 349-13, and ensuring that the strength is governed by a ductile steel element, in this case the anchor bolt. The design indicated that 10 anchor bolts would be sufficient to withstand the computed equivalent lateral load from a severe seismic event of 271 kN, based on the expected spectral accelerations of the DSC. The final anchorage design is shown in Fig. 7 along with the bolt numbering sequence and direction of loading. The inner diameter of the clamp ring was made



(a) (b)

Fig. 7 – Anchored Cask: (a) Clamp Assembly with Cask; (b) Clamp Assembly Plan View



(a) (b)

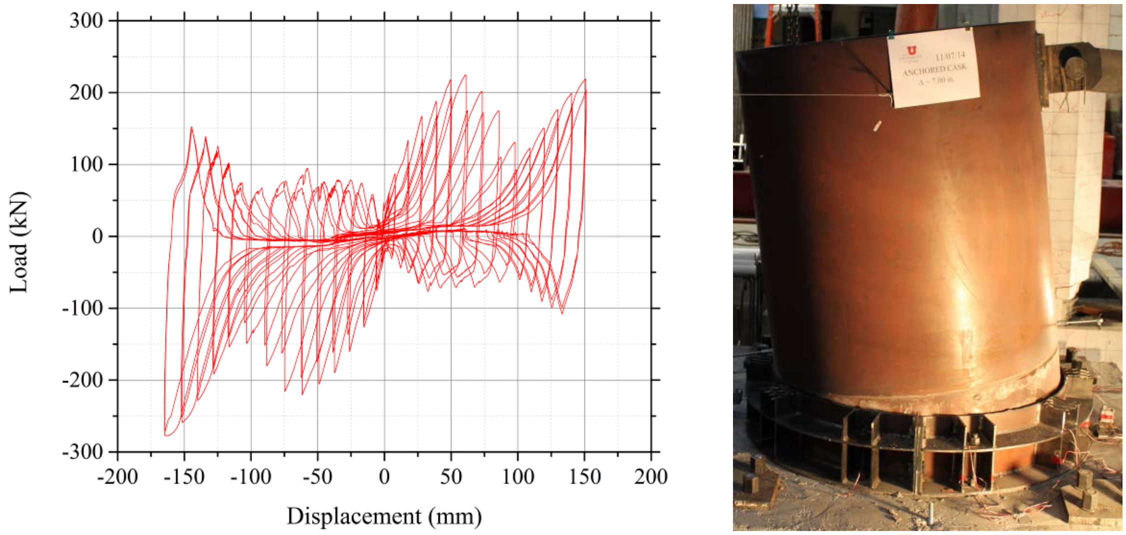
Fig. 8 – Anchored Cask Cyclic Test: (a) Anchored Cask Test Setup; (b) Loading Protocol

slightly larger than the diameter of the DSC to allow easier installation of the clamp ring; the inner diameter of the clamp ring was 1,067 mm leaving a gap of 6.4 mm between the clamp ring and the DSC. This 6.4 mm gap was filled with a high flow grout that had a compressive strength equal to 87 MPa on the day of the test.

The test setup for the anchored DSC test is shown in Fig. 8(a). The lateral load was applied at the mass centroidal height of the scaled DSC to represent the overturning moment it would experience in a seismic event. Since the load is applied at the center of mass, the height of the DSC for this test was reduced to 1,372 mm. The cyclic loading protocol for the anchored DSC is shown in Fig. 8(b).

As observed from the hysteretic response of Fig. 9(a), essentially two different experiments were performed: (i) when grout was present in the gap between the clamp ring and cask, and (ii) when there was no grout in the gap. After the 63.5 mm displacement step, the grout in the gap between the DSC and clamp ring began to pulverize leaving a void where the grout once was. As the grout began to crush, a drop in lateral load was observed until the grout pulverized leaving a 6.4 mm gap between the clamp ring and DSC. Once the grout had pulverized, a large lateral displacement was needed to wedge the DSC in the clamp ring. This occurred at a displacement of 114 mm as the load begun to increase once more. This response was unexpected, because instead of the DSC and clamp ring showing composite action, the two components behaved independently, as shown in Fig. 9(b); the cask displaced 178 mm while the clamp ring remained stationary. Thus the clamp ring successfully restrained the DSC from moving horizontally, but provided very little vertical restraint; the latter was due to friction between the DSC and the ring. After the 178 mm displacement step the test was terminated.

Due to the non-composite performance of the system it was determined that a retrofit of the ring design was needed to develop composite action. Then, steel stiffeners were welded to the cask and vertical top plates of the ring, as shown in Fig. 10, to ensure that the DSC and ring act compositely. This method is more representative of a newly constructed DSC, because existing casks cannot be welded. The cask was retested quasi-statically in the same manner as the original.



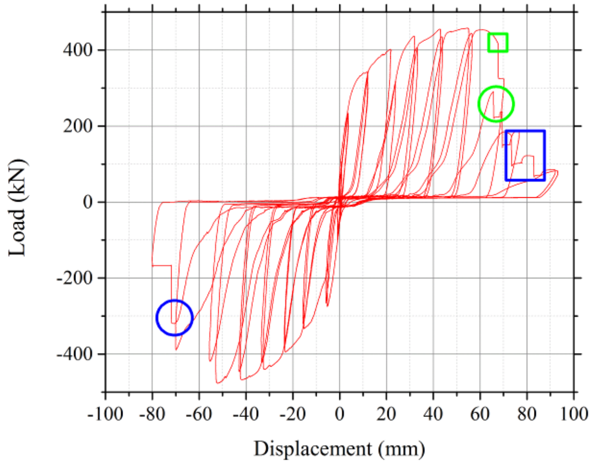
(a) (b)

Fig. 9 – Anchored DSC Results: (a) hysteretic performance; (b) non-composite action

Fig. 10 – Clamp ring retrofit

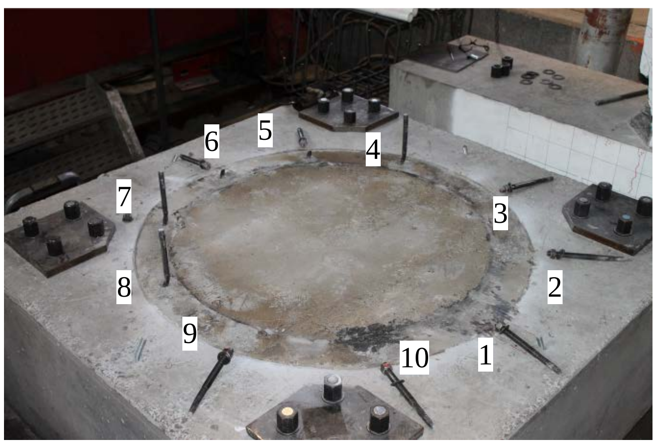
The experiments showed that composite action between the DSC and ring was achieved. Fig. 11(a) shows the hysteretic response of the retrofitted anchored DSC, which is different than that of the previous experiment due to the composite action between the DSC and ring. This is evident by the increased lateral load from about 280 to 476 kN, as well as the flag shaped hysteretic response. Composite action between the DSC and ring is also evident in Fig. 11(b) since no relative movement between the cask and the clamp ring was observed. The flag shaped response is caused by anchor bolts that do not experience compression loading. As the rotation of the cask increases due to the overturning moment, the bolts begin to elongate in tension. Thus, once the maximum displacement is reached and the cask begins to move in the opposite direction, there is almost no lateral load capacity until the rotation of the cask is large enough to engage the nut of the bolts.

During the first cycle of the +63.5 mm displacement step, failure of the extreme east anchor bolt, Bolt 1, occurred as denoted by a green square in Fig. 11(a). In the second cycle of the +63.5 mm displacement step, Bolts 2 and 10 failed almost simultaneously and this event is denoted by a green circle in Fig. 11(a). Failure of these 3 bolts resulted in a lateral load capacity drop greater than 20%. Testing resulted in failure of Bolts 3 and 9 during the first cycle of the 76.2 mm displacement step, and failure of Bolts 5 and 6 a half cycle latter. These events are denoted by a blue square and blue circle respectively; Bolts 5 and 6 failed in shear after bolts 1, 2, 3, 9, and 10 failed in tension. Fig. 12(a) shows bolts that had failed during the test. Inspection of the DSC after testing showed no damage while the clamp ring showed severe structural damage. Damage to the clamp ring included buckling of the vertical side plates at Bolts 1 and 6, along with top plate yielding at all bolts. Fig. 12(b) and 12(c) show clamp ring damage at Bolts 1 and 6, respectively.



(a) (b)

Fig. 11 – Anchored DSC Retrofit Results: (a) Hysteretic performance; (b) Composite action



(a) (b) (c)

Fig. 12 – Anchored Cask Damage: (a) Bolt Failures; (b) Chair 1 damage; (c) Chair 6 damage

Figure 13 compares the hysteretic energy dissipation of the two anchored DSCs tests. Interestingly, the original anchored DSC dissipated more hysteretic energy after every cycle when compared to the retrofitted DSC even though the lateral load was much higher for the retrofitted DSC. The reason is that in the retrofitted case the hysteretic loops are very narrow because the fact that anchor bolts are never under compression. Therefore, even though there is a large lateral load, the area of the loop is relatively small. On the other hand for the original anchored DSC the energy dissipation comes from friction between the DSC and the ring. Since friction is the source of energy dissipation it creates “fatter” hysteretic loops, thus producing greater energy dissipation.

3.1 Shake Table Experiments

A 1:2.5 scaled DSC anchored with a welded steel ring configuration was tested on a biaxial shake table at the University of Nevada, Reno. For the shake table experiments both conventional and stretch length anchors with an 8 db stretch length were tested. The anchored DSCs were subjected to two ground motion types with one representing a near field ground motion (NFGM) and the other representing a far field ground motion (FFGM). The NFGM is Erzikan (1992) and the FFGM is Chi Chi (1999). These motions were spectrally matched to hazard level and spectral acceleration for seismic events up to a 30,000 year return period.

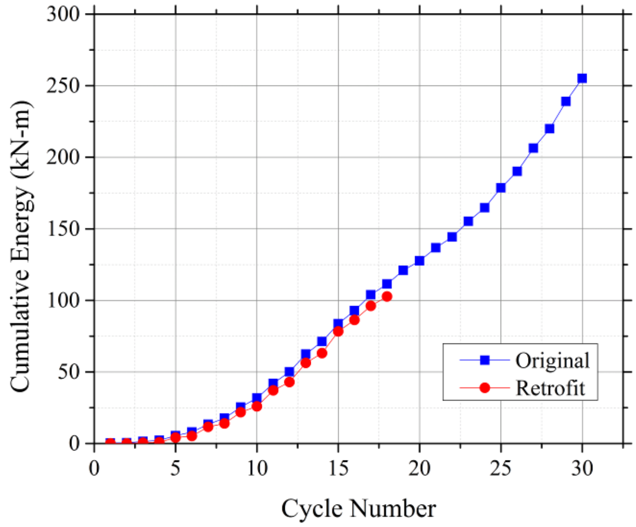


Fig. 13 – Anchored Cask Energy Dissipation Comparison

Time histories for NFGM and FFGM are shown in Figs. 14a and 14b, respectively. The NFGM, Erzican, is characterized by a large pulse with a peak ground acceleration (PGA) of 1.42g and a short duration of about 13 seconds. The FFGM, Chi Chi, had a longer duration of about 45 seconds and a PGA of 0.93g. Acceleration time histories (ATHs) of the top of the cask for conventional and stretch length anchors are presented in Fig. 15 and 16, respectively. During these ATHs no failure of the anchor bolts occurred. However, permanent elongation of the anchor bolts occurred for both anchor types, along with buckling of the bottom plate for conventional anchors, and buckling of the top plate for stretch length anchors. In terms of acceleration at the top of the cask both anchor types showed similar performance. For the Erzican ground motion, the conventional anchor case had a maximum top of the cask acceleration 1.068 times larger than the stretch length anchor case. For the Chi Chi ground motion the stretch length anchor case had a maximum top of the cask acceleration 1.084 times larger than that of the conventional anchor case.

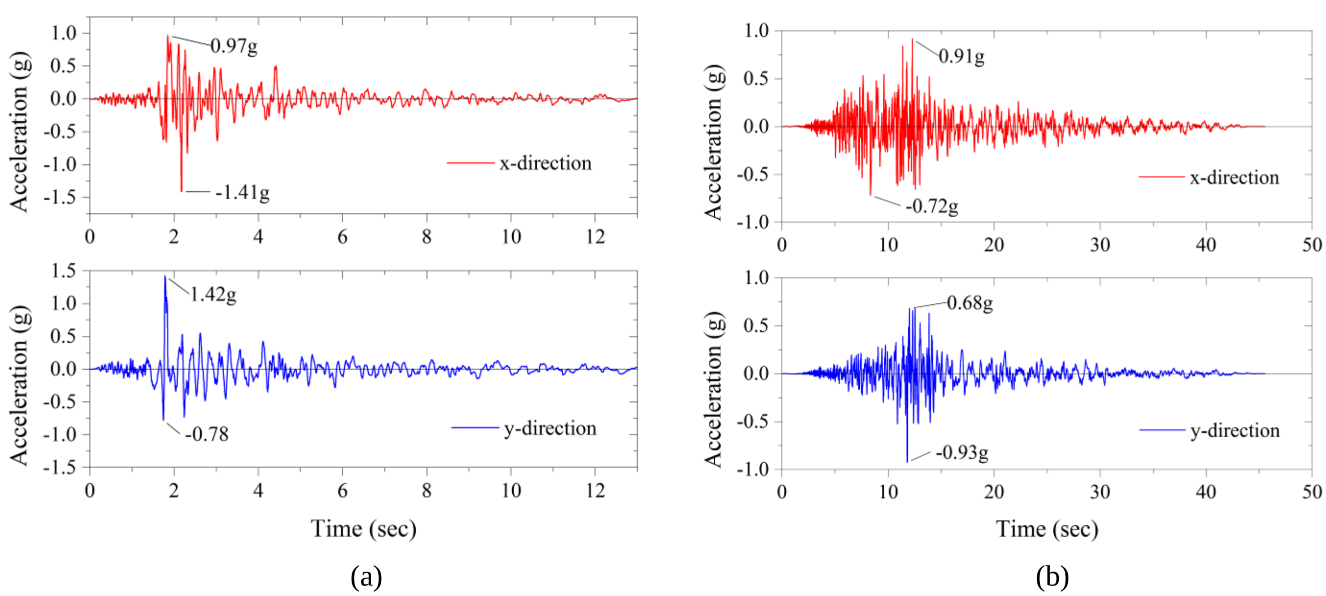
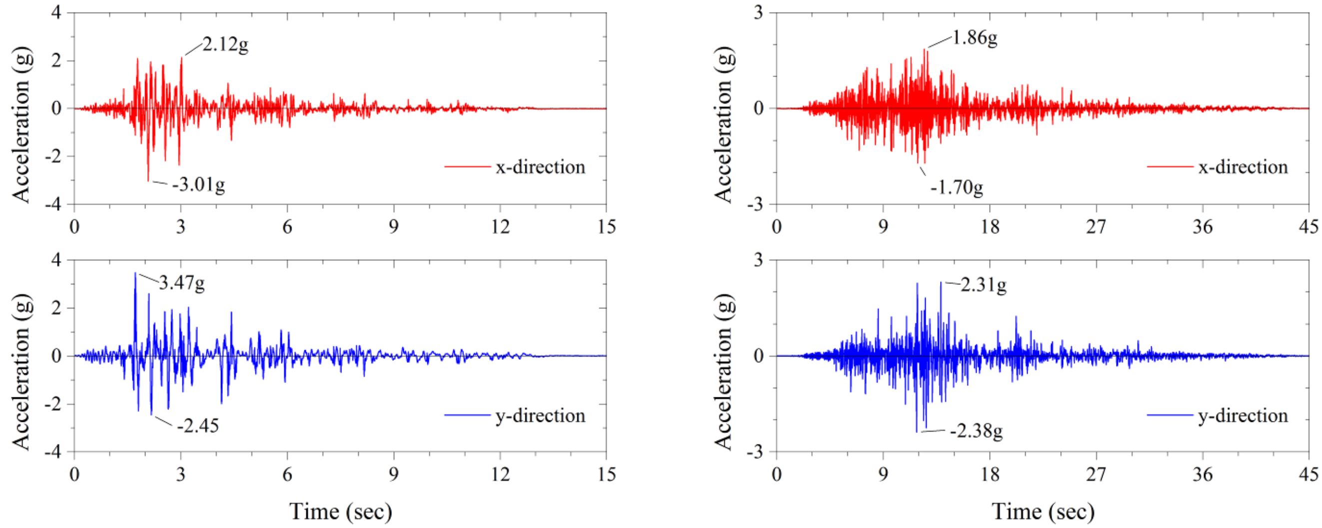
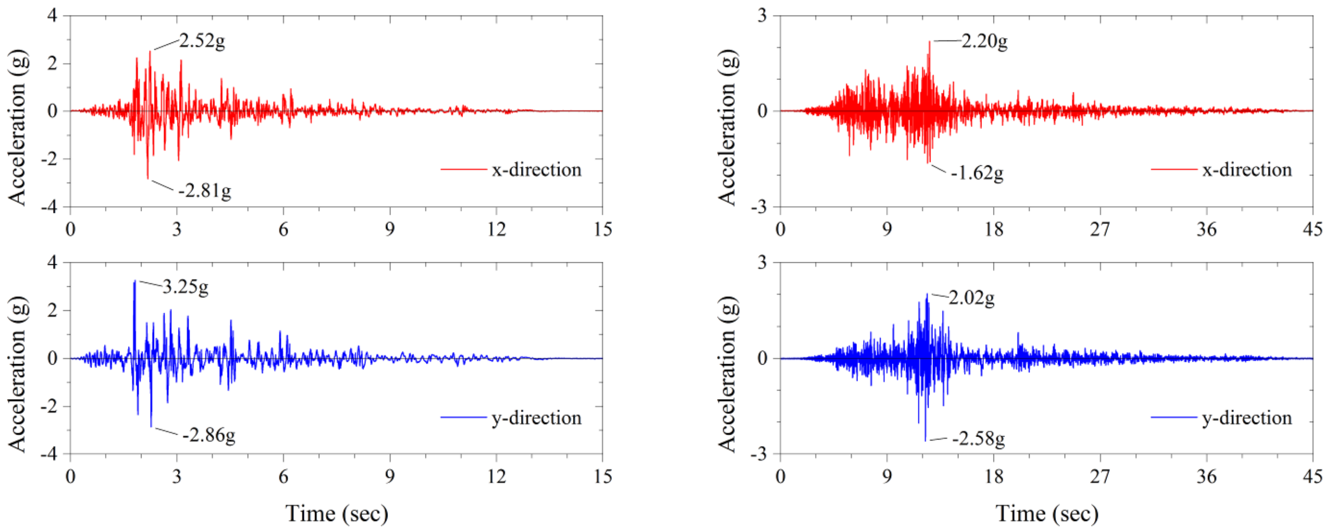


Fig. 14 – Shake Table Ground Motions: (a) Erzican [NFGM]; (b) Chi Chi [FFGM]



(a) (b)

Fig. 15 – Conventional Anchor Acceleration Time History: (a) Erzican [NFGM]; (b) Chi Chi [FFGM]



(a) (b)

Fig. 16 – Stretch Length Anchor Acceleration Time History: (a) Erzican [NFGM]; (b) Chi Chi [FFGM]

4. Conclusions

Sixteen single anchor tests were performed with anchor bolts in combined tension and shear. From these tests it was found that by providing a stretch length, a significant increase in tensile displacement capacity can be achieved compared to a conventional type anchor. By decreasing the stretch length from the code specified 8 db no decrease in the tensile displacement capacity of the anchor was observed. This result is mainly attributed to the concentration of stresses (shear and tension) at the concrete interface resulting in similar failure displacements regardless of the stretch length. When providing a steel chair that yields, an increase in the tensile displacement capacity occurs for all cases. This increase is due to buckling of the bottom plate for conventional anchors and that of the top plate for stretch length anchors. Buckling of the plate reduces the displacement demand on the anchor bolt enabling a greater displacement to be reached. However, buckling of the plates results in permanent damage the steel chair, making replacement of the chair necessary.

From the findings of the single anchor tests it was decided that the DSC would be anchored with bolts having a stretch length of eight bar diameters and a steel clamp ring allowed to yield. The results of the DSC with the free ring configuration showed that the anchorage system worked well at restraining the cask in the horizontal direction, however it provided little resistance in the vertical direction due to lack of composite action between the DSC and steel clamp ring. A retrofit of the steel ring was carried out by welding additional stiffeners from the ring to the DSC to ensure composite action, and the anchorage system was re-tested. The welded ring configuration achieved full composite action between the steel ring and the DSC, resulting in an anchorage system that exhibited ductile performance while restraining the cask in both the horizontal and vertical directions.

For the shake table experiments both conventional and stretch length anchors with an 8 db stretch length were tested. The anchored DSCs were subjected to two ground motion types with one representing a near field ground motion (NFGM) and the other representing a far field ground motion (FFGM). During these dynamic tests, no failure of the anchor bolts occurred. However, permanent elongation of the anchor bolts for both anchor types occurred with buckling of the bottom plate for conventional anchors and buckling of the top plate for stretch length anchors. In terms of acceleration at the top of the cask both anchor types showed similar performance. For the Erzican ground motion, the conventional anchor case had a maximum top of the cask acceleration 1.068 times larger than the stretch length anchor case. For the Chi Chi ground motion the stretch length anchor case had a maximum top of the cask acceleration 1.084 times larger than the conventional anchor case.

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