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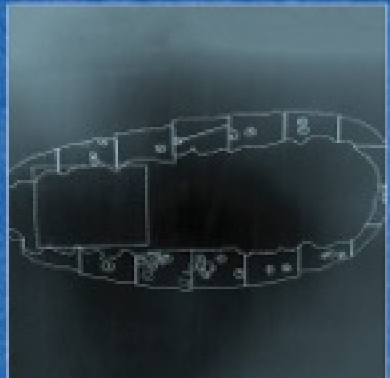

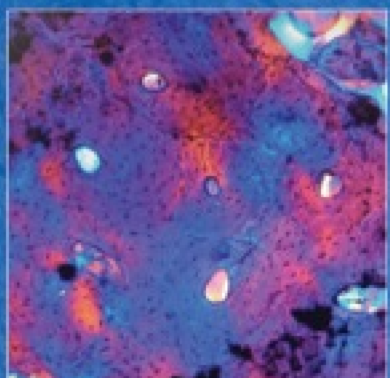

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Seismic Response of Interlocking Spiral Reinforced Columns

Eric Nguyen

Mentor: Stephen A. Mahin, Ph.D.
Department of Civil and Environmental Engineering

Abstract

This report describes a joint US-Japan research effort in 2006 between UC Berkeley and the Tokyo Institute of Technology to study the seismic design and safety of bridge columns. The study simulated and compared the strength and failure modes of a novel bridge column design against a more conventional design by subjecting both to several historical earthquake ground motions. This report was written prior to the design, fabrication and testing of model-size columns completed in 2007.

For a bridge to be seismically resistant, the columns must be able to resist heavy lateral forces. To resist these forces and the high shear, horizontal reinforcement is provided in the column. The reinforcement also serves to confine the concrete by holding the shape of the concrete and resisting the outward spread. Conventional methods of placing the reinforcement allow square and circular cross-sectioned columns to have ties or spiral reinforcement. Rectangular cross sections are restricted to ties because of the geometry and constructability of the reinforcement. However, it has been shown experimentally that spiral reinforcement is more effective in providing shear capacity (Jaafar & Morley, 2003). This is followed by smaller strength reduction factors in design, for example by the American Concrete Institute (ACI). This report analyzes the interlocking spiral reinforcement for implementation in rectangular columns.

Background of Spiral Reinforced Columns

A significant advantage of the spiral reinforcement is the higher level of confinement it provides for the concrete. Due to the natural tendency for materials and fluids to disperse in a radial direction, the circular spiral reinforcement is more efficient in maintaining the shape of the concrete. Furthermore, spiral reinforcement is continuous throughout the height of the column and makes construction simpler.

Although the strength reduction factor is higher for ties, the level of confinement may have different impacts on the inelastic response of the column. Spalling occurs when the cover concrete not withheld in the reinforcement cracks off and weakens the column. The spalling for the concrete will be higher in the tie system, which will mean higher costs in repair after a seismic event. Furthermore, the cost of fabrication is higher for the ties. Bridges often need rectangular cross section due to the different load demands in separate directions, and this has led for design of rectangular columns to include spiral reinforcement.

The implementation of spiral reinforcement in rectangular columns consists of overlapping 2 or more spiral reinforcement cages at the center to create an interlocking system that would allow for varying rectangular sections. This method provides the benefits of efficient shear strength and confinement to sections previously restricted to ties only. The method was first adopted by the American Association of State Highway and Transportation Officials (AASHTO) in 1971 and then revised in 1990 by the California Department of Transportation (Caltrans). However, these provisions and design codes are based on limited research and conventional column design of single spiral reinforcements. A number of bridges in New Zealand and Japan had adopted these methods and had similar design based on these codes. The design provisions were done using conventional column design and could conservatively analyze and design the interlocking columns. However, more accurate and specific design parameters must be quantified to provide efficient and reliable design criteria for their use in large scale.

In the past few years, government transportation agencies have realized the benefits of the interlocking system and have funded more research studying the most important parameters. The first testing of interlocking columns was done by Tanaka and Park (1993) where 3 interlocking and 1 conventional spiral columns were built at 1/6 scale. They investigated the performance of the interlocking columns in shear and lateral confining capacities. The interlocking columns displayed good energy dissipation and low strength degradation, which confirmed the adequacy of the system.

In a study done by Buckingham et. al (1993), shear, flexural and shear capacities were investigated experimentally. The specimens were fabricated at 1/5 scale with varying spiral and tie reinforcement, spiral overlap, and the size of longitudinal bars in the interlocking region. The columns were subjected to increasing cyclic inelastic displacements and evaluated in terms of lateral load capacity, strength degradation, energy dissipation, and failure mechanisms. In all cases, the interlocking columns performed as well or better than the tied columns, despite having half the transverse reinforcement ratio. They found that performance increased when the interlocking distance was restricted to 0.6 the diameter of the spiral. Four bars in the interlocking region the same size as the outside bars were required to transfer the load between the spirals. This maintained the interlocking of the columns even during large displacements.

A study done by Mizugami (2000) investigated different volume ratios of the interlocking columns that had different modes of failure. Their experiments indicated no brittle shear failures, which is a requirement in seismic design. They found that interlocking columns had the same capacity as tied columns with 300% more transverse reinforcement. The results allowed their group to make recommendations on the volumetric ratio of the spirals for design.

Design of interlocking columns was strengthened by experiments done by Kim and Park (1999) who tested 108 specimens with variables of concrete strength, spiral strength, pitch, and interlocking distance. This allowed more evidence in providing design criteria. Their results showed that as the strength of concrete increased, the strain capacity of the concrete decreased. The decrease in concrete strain capacity was similar also for increasing pitch or spiral spacing. The strength and ductility of the column was enhanced with higher yield strengths of the spirals. They proposed models of strength and axial strain at peak stresses, which predicted the performance of interlocking columns.

The past research has confirmed the effectiveness of the interlocking column system. It has been shown to provide greater shear and confinement capacity while being simpler and cost-effective in construction. However, the modeling and implementation is based on little experimental data. Further investigation must quantify key parameters to provide solid design criteria for code provisions. Many of the past experiments have contributed in this regard, but lack the confirmation of actual behavior for existing structures.

A U.S. and Japan initiative has scheduled a large-scale fabrication of an interlocking column for experiment at the E-Defense shake table in Japan in the summer of 2007. This will allow researchers to confirm their predictions and analysis for the largest scale models ever tested for interlocking columns. In preparation of the full scale experiment, 4 columns cast in Tokyo will be tested at the University of California, Berkeley in September of 2006. The results of these columns will allow for the design of the large scale column at the E-Defense. The preliminary testing will provide quantification of key parameters in the interlocking columns and solidify the provisions of interlocking design.

Based on the recommendation done by the past research on interlocking columns, we fabricated two interlocking columns to further investigate the influence of the interlocking area. As a comparison, two columns with ties were fabricated according to similar yield accelerations, thus with different reinforcement ratios. This differs from past research by having fixed strengths of the columns which allows us to see which failure mechanisms are critical. In order to confirm our methods in designing interlocking columns, preliminary analysis using dynamic finite element software was used to produce predictions. In this study, a single pair of columns was investigated. Two 1/6 bridge columns were designed and analyzed to compare the seismic performance.

Methods

Design

The first step was to design the columns at 1/6 scale to desired strengths and capacities. Previous research by Buckingham et. al. (1993) has recommended the use of 4 longitudinal bars in the center. This would help secure the spiral reinforcement in place to maintain the interlocking in the column. We followed this procedure and used the same bar size throughout the column cross section. The reinforcement ratios of the interlocking and tied columns were designed to the desired strengths in flexure and shear following method of statics and approximations by American Concrete Institute (ACI). This provided estimates for strengths in shear and flexure by conventional methods which allow us to confirm our design methods by comparing these capacities with dynamic demands. Note that it was necessary to estimate the shear capacities. As such, the highly variable influence of the interlocking spirals ratios can alter the shear strengths greatly from standard design predictions.

The interlocking columns were designed with slightly higher shear reinforcement than the tied columns, but also experience higher shear stress from the experimental setup. Thus the shear demand is maintained for interlocking and tied columns. For each size, the yield acceleration is estimated to be similar. The column specifications are tabulated below.

	Interlocking	**Tied**
Column Height	2.19 m (7.19 ft)	2.19 m (7.19 ft)
Gross Area	99,200 mm^2	112,000 mm^2
Long. reinforcement	30@D10, 2.16%	26@D10, 1.66%
Transverse reinforcement	Spacing 37mm@D6, 1.16%	Spacing 37mm@D6, 1.05%
Yield acceleration	2.89 m/sec^2 (strong axis) 2.00 m/sec^2 (weak axis)	2.80 m/sec2 (strong axis) 2.00 m/sec2 (weak axis)

Figure 1. Column Design Specifications

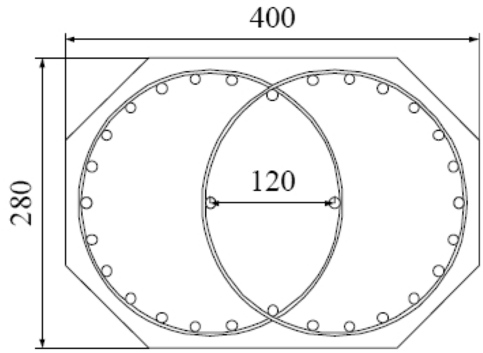


Figure 2. Interlocking Column Cross Section.

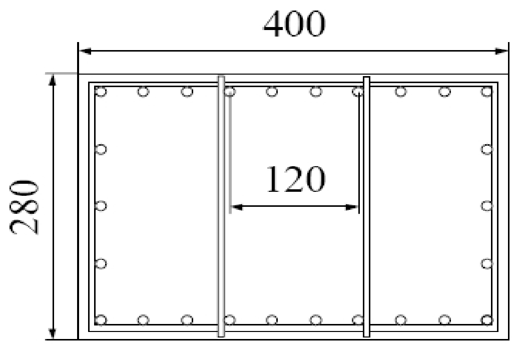


Figure 3. Tied Column Cross Section.

Experimental Setup

The columns were tested at the Richmond Field Station in Richmond, California. In the computer model, the columns were fitted with three concrete mass blocks at 227 kN as the dead load shown below. The model experienced three-dimensional motion during the excitation.

Idealization

As necessary in any model, idealization of the experiment must be made to gain prediction results. The linear beam section was assumed to remain elastic during excitation with no damage. The rigid body section was assumed rigid while also remaining elastic. The plastic hinge section at the bottom of the column was modeled as a fiber element. This allowed the stress and strain to be recorded as inelastic damage occurred.

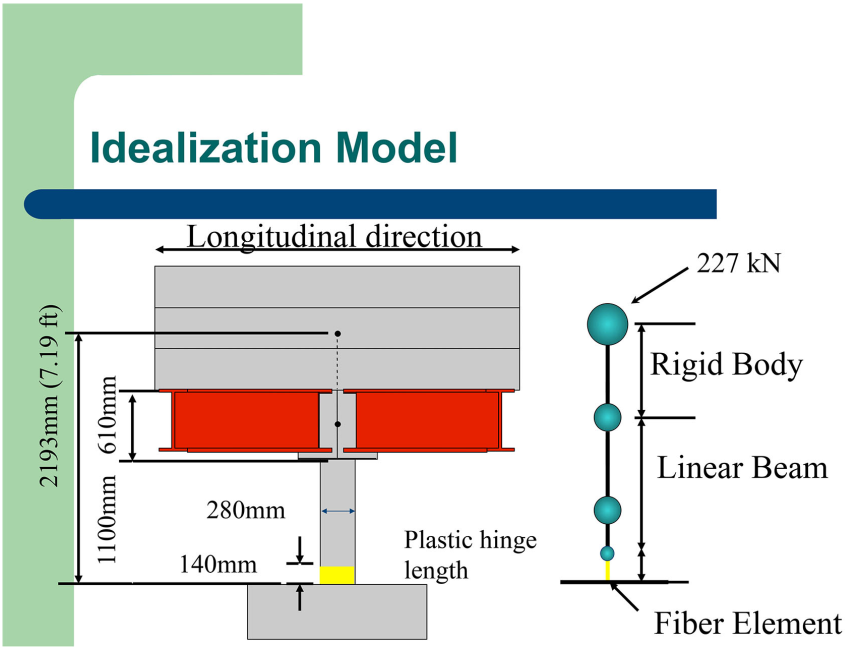


Figure 4. Idealization of Experiment.

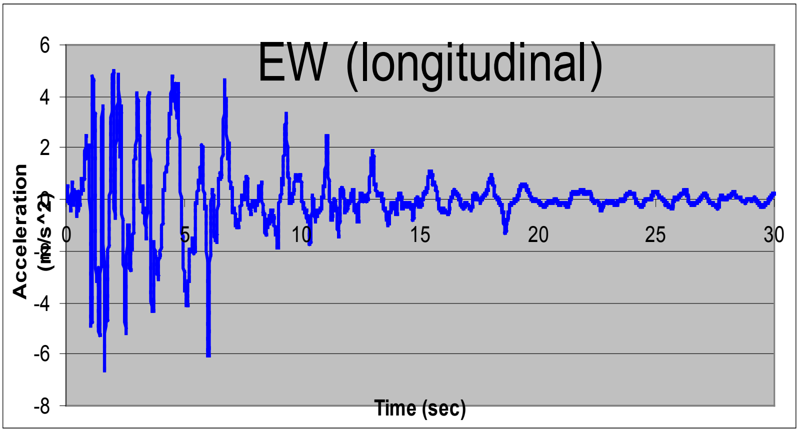
Computer Modeling

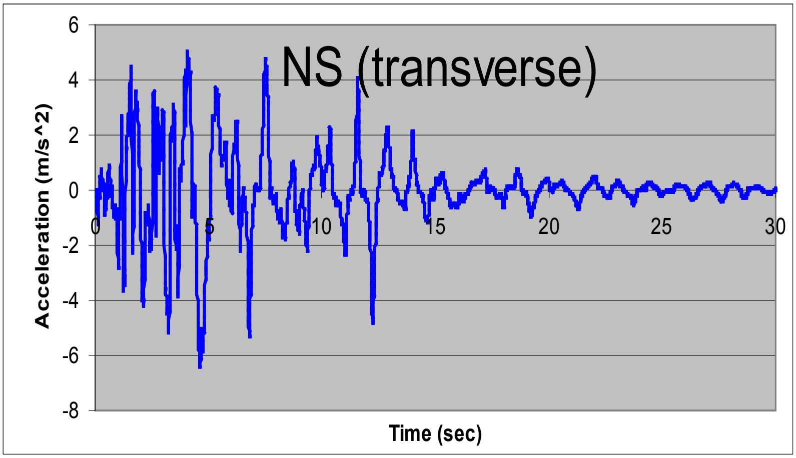
OpenSEES was used to model the experiment. The program is widely used at the Pacific Earthquake Engineering Research (PEER) Center and is regarded as UC Berkeley's premiere earthquake software. The concrete was modeled using Kent-Scott-Park concrete model. The steel was idealized using the Bi-linear model.

The transverse reinforcement was not modeled directly. The transverse reinforcement confined the core concrete and had higher compressive and strain values than the unconfined concrete. However, the shear could not be modeled and shear failure was not analyzed because the transverse reinforcement was not directly modeled. Buckling of the longitudinal reinforcement was not assumed as a mode of failure in order to simplify the analysis.

Ground Motions

The 1995, Kobe earthquake ground motions were used at the JR Takatori station. The peak ground acceleration was 0.68g in the longitudinal component and 0.65g in the transverse component. The vertical component was insignificant for our purposes of analyzing seismic because lateral excitation was the main cause of damage in earthquakes.





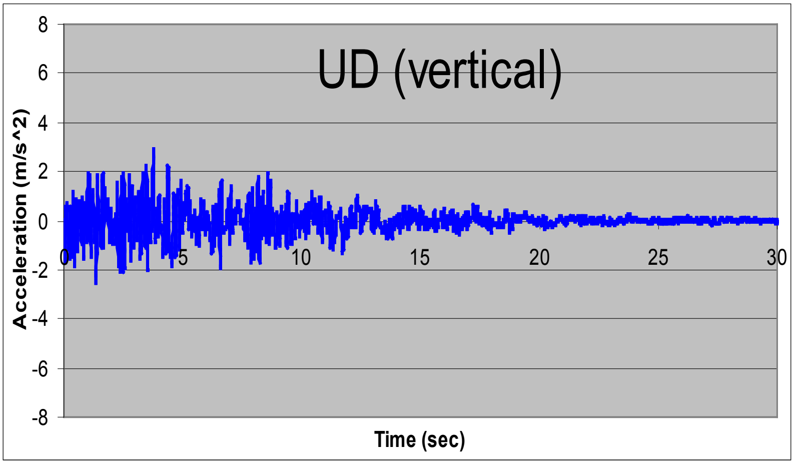


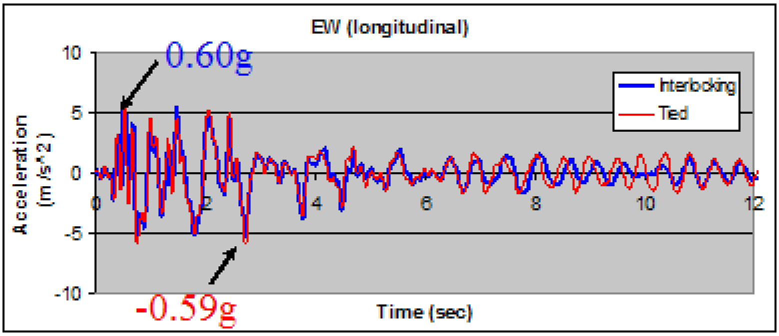
Figure 5. Kobe Ground Motions.

Output

From the results of the dynamic analysis, we compared the tied and interlocking columns performance. This allowed us to generate graphs such as moment vs. curvature, lateral force vs. displacement, acceleration vs. time, displacement vs. time and the ultimate moment.

Results & Discussion

The acceleration at the center of the mass block was recorded and is a measurement of the motion experienced at the bridge deck. The east-west component is longitudinal to the bridge. The transverse direction is the strong axis to the column and therefore has a higher capacity. The interlocking and tied columns have nearly identical acceleration response. This means the movement at the bridge deck is similar for both columns.



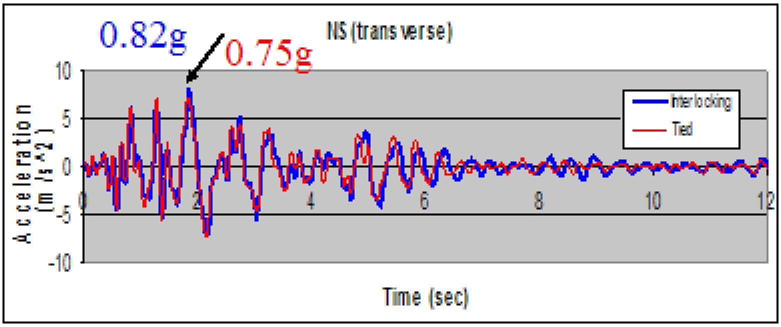


Figure 6. Acceleration vs. Time at Center of Mass Block.

	Acceleration Longitudnal	Acceleration Transverse
Interlocking	0.60g	0.82g
Tied	-0.59g	0.75g

Figure 7. Table of Maximum Acceleration Response at Center of Mass Block.

The displacement at the center of the mass block shows us how far the bridge deck will move during the earthquake and is a type of indication of the damage. The larger displacements can cause higher damage. The interlocking and tied columns showed similar results for displacement also.

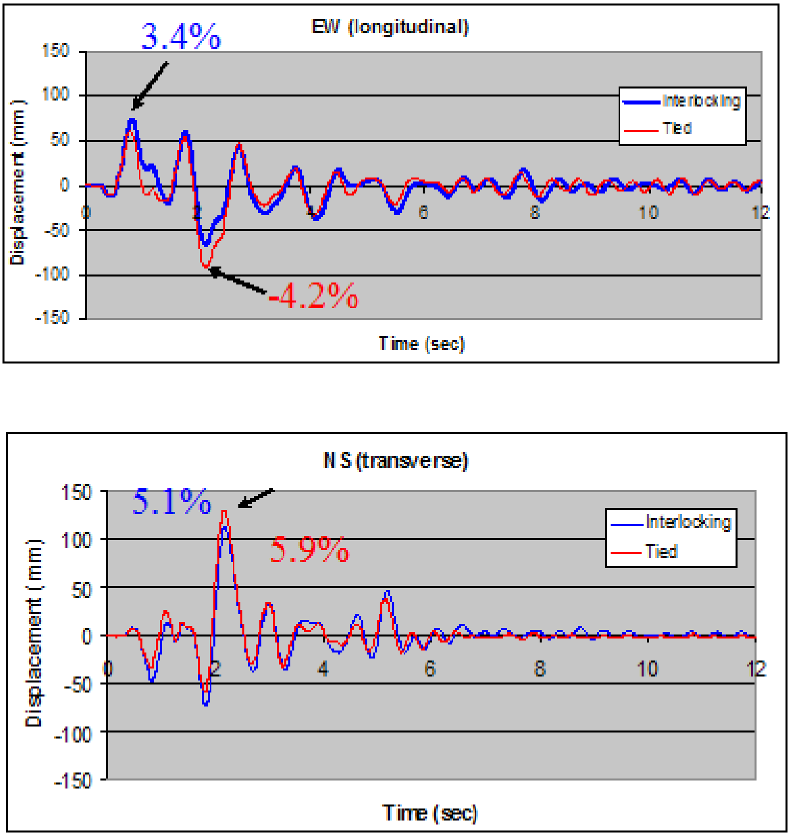


Figure 8. Displacement vs. time at Center of Mass Block.

	Drift Longitudnal	Drift Transverse
Interlocking	3.4 %	5.1 %
Tied	-4.2 %	5.9 %

Figure 9. Table of Maximum Drift Ratio at Center of Mass Block.

The plastic hinge region of the column was the location that we are interested the most in order to analyze the damage. The moment vs.

curvature allows us to see the response of the column as it is subjected to higher moments. From the graph, we observed that the tied column experienced more damage due to the higher curvature. This was a result of having damage in a concentrated area which created a weak spot for more damage to propagate. This was observed from the higher damage only on one side of the graph (the positive) for the longitudinal direction. However, the tied column had higher moment capacity than the interlocking column. In the transverse direction both columns had concentrated damage but the tied column had higher moment capacity than the interlocking column.

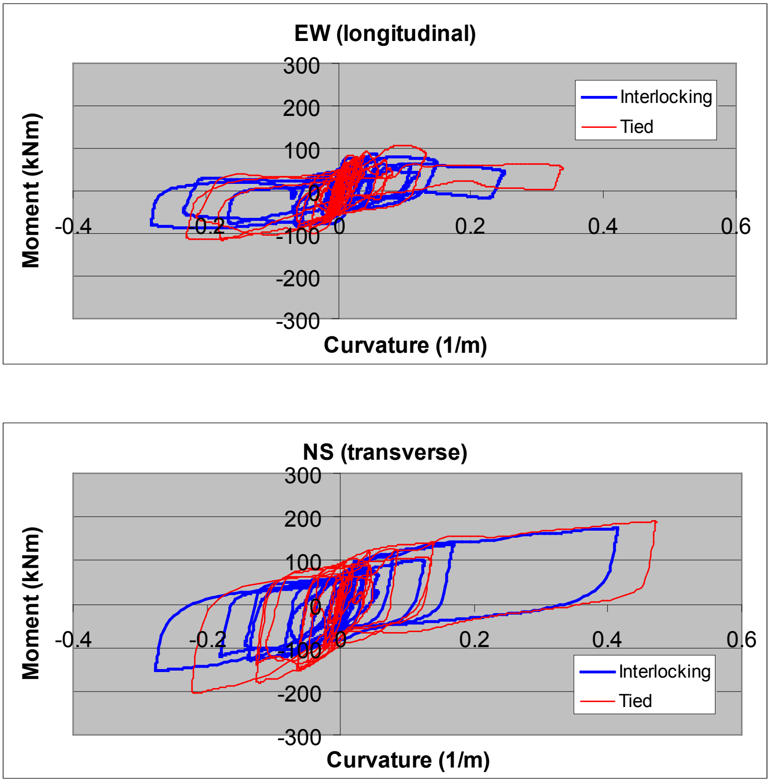
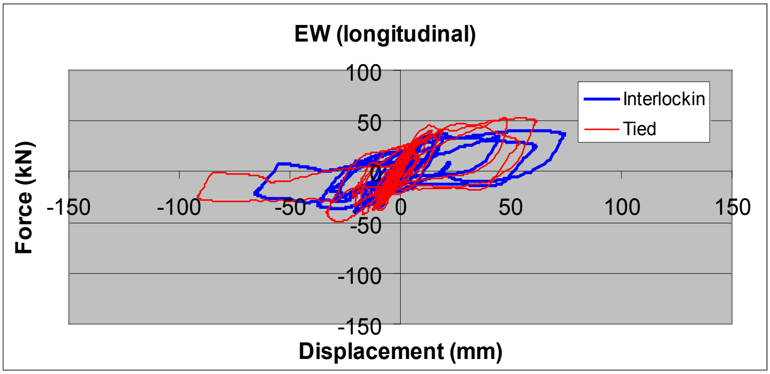


Figure 10. Moment vs. Curvature at hinge.

	Ultimate Moment (kN*m) Longitudinal	Ultimate Moment (kN*m) Transverse
Interlocking	108	126
Tied	150	204

Figure 11. Table of Ultimate Moment Capacity.

The lateral force vs. displacement graph is also a measurement of the damage at the plastic hinge region. In the longitudinal direction the tied column experienced heavy concentrated damage (negative) causing a decrease in lateral force capacity. However, the tied column ultimately had a higher lateral force capacity. There was similar behavior in the transverse direction, but to a higher degree and damage in the positive displacement component.



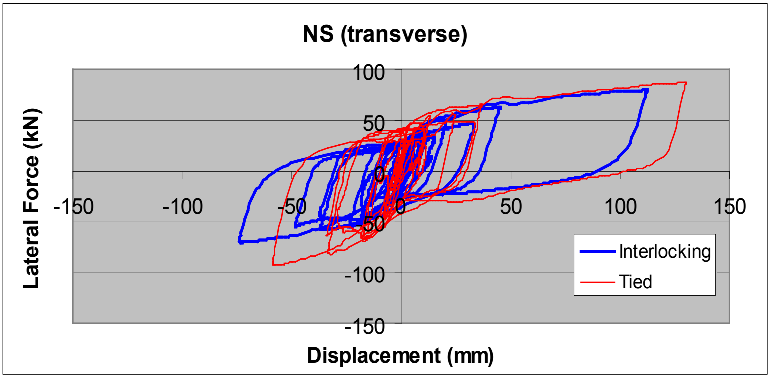


Figure 12. Lateral Force vs. Displacement.

The difference in the interlocking and tied columns can be due to many reasons. The columns have different arrangement of longitudinal bars which although may have similar moment capacities statically, the dynamic response can lead to different damages. This was shown in the tied column where there was larger displacement in a particular region of the column. Also the slight difference in natural periods of the columns can cause different dynamic response. This is due to the many frequencies in earthquake motions which forces different responses to different natural swaying of the column.

These results assumed that shear failure of buckling has not occurred. Though this may be possible before the ultimate moment of the column, it is not known for sure. Experimental results are needed to see if these modes of failure dictate. The accuracy of the models used in this analysis can then be verified. However, the accuracy of the confined concrete model has been used in past research and shown to be accurate. This is expected to decrease the damage on the interlocking column during the experiment.

Limitations

Although the analysis provides comprehensive results for the interlocking and tied columns, they are preliminary results. The transverse reinforcement was not put into account directly. This meant shear was not able to be modeled and thus shear failure was not analyzed. Buckling is another failure mode that cannot be modeled because of the complexity of the event. Furthermore, the analysis is as only good as the models used and their idealized assumptions. The material models are as good as any other models but still vary somewhat from model to model. Torsion is assumed to not be a factor but during a test this is usually the case. With these limitations, OpenSEES has shown fairly accurate results with many engineering parameters when compared to experimental data.

Conclusions

From the modeling results, we found that the tied column experienced larger deformation. Despite this, the tied column had higher strength in moment and lateral force. Due to the limitation of shear and buckling modeling, which are fairly common, the various modes of failure could not be predicted or analyzed. Consequently, experimental results must be gathered to verify the accuracy of our model since interlocking columns are relatively premature to be modeled correctly. Despite the interlocking column being weaker in ultimate moment capacity, the contribution of spiral confinement is predicted to produce less damage during inelastic loading in the actual experiment for the interlocking column.

Works Cited

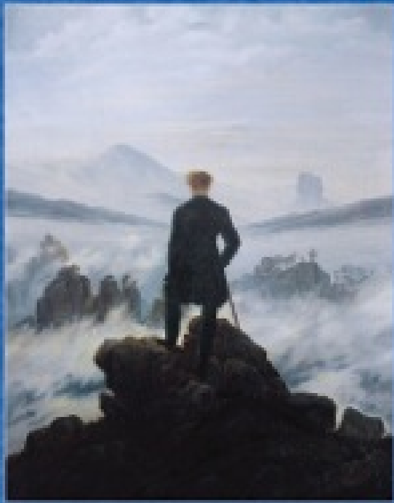
Buckingham G.C., McLean D.I., and Nelson C. Tests of concrete bridge columns with interlocking spiral reinforcement. *Transportation Research Record*, 1993, No. 1393, 133-145.

Jaafar K. and Morley C. Seismic behavior of rectangular concrete beams with spirals near potential plastic hinges. *Advances in Earthquake Engineering*, v 13, Earth Resistant Engineering Structures IV, 2003, 121-130.

Kim J. K. and Park C.K. The Behavior of concrete columns with interlocking spirals. *Engineering Structures*, October 1999, 21, No. 11, 945-953.

Mizugami, Y. Efficiency of lateral reinforcement in interlocking spirals rebar, *16th US-Japan Bridge Engineering Workshop*, October 2000, 265-276.

Tanaka, H. and Park R. Seismic design and behavior of reinforced concrete columns with interlocking spirals. *ACI Structural Journal*, March-April 1993, 90, No. 2, 192-203.



This painting is quite the perfect metaphor for what our research projects have been about: an effort to 'master' the laws of our social and natural environment by ordering them according to human systems of knowledge like sociology or biology or literature; it is an effort that originates from the wonder of all we still don't know about the world." The above image is a painting by Caspar Friedrich titled *Wanderer Above the Sea of Fog* and connects to Journal author Armen Davoudian's article in his analysis of Moore's poem, *A Grave*. Upon reflection, Armen offered this quote to symbolize the journey that all of the Journal contributors have undergone.

The front cover illuminates the true diversity of the Berkeley McNair Research Journal. Beginning from the top left, is a photograph of the fields of Watsonville, California where Natalie Solares collected samples of organic strawberry plants. Next are three images Brian Vassalo captured for his research on bone histology of juvenile rib sections, under varying degrees of magnification. Lastly is a historic photograph of Merritt College students on strike to protest the relocation of their campus to the Oakland Hills, described in the research of Rasheed El Shabazz. This collage portrays the multifaceted research presented in this Journal over the last 21 years.

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