NCHRP 12-74 DEVELOPMENT OF PRECAST BENT CAP SYSTEMS FOR SEISMIC REGIONS – SYSTEMS DEVELOPED FOR FURTHER INVESTIGATION

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ABSTRACT

The desire to reduce public and environmental impacts and accelerate construction has led many agencies to consider the use of precast substructure systems on bridge construction projects. Precast bent caps offer the advantage of improving quality and safety while also reducing construction time and impact to the environment. The National Cooperative Highway Research Program is funding Project 12-74, "Development of Precast Bent Cap Systems for Seismic Regions," to develop and validate promising precast bent cap systems and to generate design and construction specifications for use in all of the nation's seismic regions. A summary of results from a recent comprehensive survey of DOT officials, engineers, fabricators, and contractors is provided, including an overview of current precast bent cap usage throughout the world. A review of expected seismic performance, constructability, durability, and economics is presented for the details which have been proposed for further investigation in this project. An overview of future research activities including strut-and-tie models, beam-column tests, large-scale system test, and time-history analyses will be provided.

Keywords: Substructure, Precast, Seismic Design/Retrofit, Rapid Construction, Research

INTRODUCTION

A large quantity of bridges throughout the country is in need or repair or replacement as they are structurally deficient or functionally obsolete. These structures must be replaced while traffic operation continues, as many of the bridges serve as vital links in the transportation network. Precast concrete bent caps provide a means to accelerate bridge construction by removing much of the work from the critical path. Accelerated construction is just one advantage of precast bent caps. Environmental impacts can be reduced due to a decrease in time on site and because much of the environmentally hazardous operations are moved to a less intrusive location. Quality of bent cap members can also increase as they are fabricated in more controlled environments. The reduction in time on site will also improve worker safety through a reduction to hazardous site conditions. Many times, precast bent caps can also be more economic[1].

Precast bent caps have seen use in non-seismic applications in order to meet a variety of project objectives. Seismic applications, however, have been scarce. A paramount problem with utilizing precast bent caps in seismic regions is the importance of connections made between members. These connections are essential in order to ensure the desired seismic response is achieved. Uncertainty as to how these connections will behave, coupled with the lack of design guidance, has led many agencies to restrict the use of precast bent caps in high seismicity.

The National Cooperative Highway Research Program (NCHRP) is funding Project 12-74, "Development of Precast Bent Cap Systems for Seismic Regions" to create validated design and construction specifications for use in all regions of seismicity. The desired result of this study is to develop products which are immediately implementable throughout the country. Research efforts include a review of relevant research and past practice, development of connection concepts, analytical and experimental work, and development of proposed design and construction specifications. The focus of this paper is on the review of relevant research and past practice and the connection concepts.

SEISMIC DESIGN CRITERIA

Current AASHTO seismic design criteria can be traced back to the research performed as a part of ATC 6[2]. This study was representative of the current state of knowledge at that time. The AASHTO seismic design criteria have not undergone any significant changes representative of the current understanding of seismic response of bridge systems since that time. Understanding the significant advances in seismic bridge engineering, Project 12-49 was funded by NCHRP in order to modify the existing design criteria based on current knowledge; however, these recommendations were not incorporated into the design standards[3]. More recently, NCHRP sponsored Project 20-07 Task 193 in order to modify the specifications developed under NCHRP 12-49 such that they are ready for inclusion in LRFD specifications[4]. The guidelines being developed under Task 193 are being utilized in the current research program to ensure all products developed will be in line with changes to LRFD design specifications.

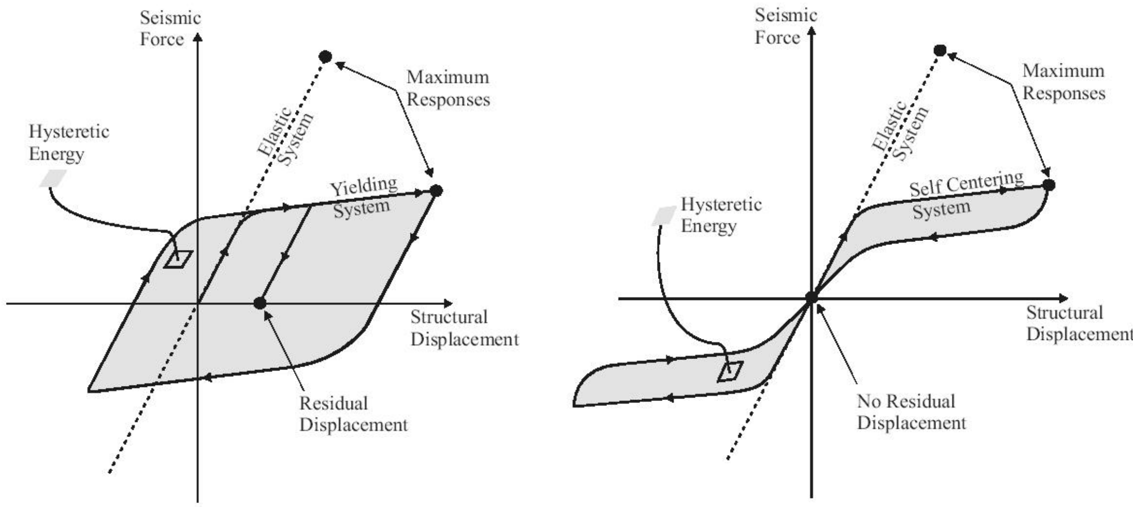
BENT CAP TYPES

Traditional beliefs dictate that the best seismic lateral force resisting system used in bridge construction is one that exhibits large energy dissipation through inelastic action in supporting bridge columns. Modern advances in seismic design have indicated that excellent seismic resistance can also be achieved through what can be described as "jointed" or "hybrid" bridge piers[5]. These systems use unbonded post-tensioning to produce a system which will self-center following a seismic event, while exhibiting significantly less damage than a comparable cast-in-place system. Precast bent cap systems have been developed which are aimed at providing seismic resistance in a similar manner to these two methods. The precast systems will be defined as emulative or jointed.

Emulative systems are designed to perform similar to, or "emulate," the behavior of a traditional cast-in-place system. The end goal is to focus inelastic action to targeted locations in well confined regions of the columns. Generalized hysteric response of an emulative system is shown in Figure 1a. This hysteretic response is believed to provide a stable form of energy dissipation; however, a major drawback to such a system is the reliance on inelastic action of the column. This signifies significant damage must occur in order for energy to be dissipated. The resulting damage can leave a structure inoperable or even near collapse following an earthquake. There is a clear trade-off, where a stable form of energy dissipation comes at the expense of significant structural damage.

Jointed systems do not rely on energy dissipation from plastic hinging in supporting columns. Instead, inelastic response is in the form of concentrated rotations about the column ends. The columns themselves remain essentially elastic with only minor damage following a seismic event. Lateral response of a jointed system can be termed "controlled rocking." Damage which comes due to seismic action is typically in the form of minor damage caused by impacting during the rocking action. Column ends must be properly detailed to ensure large compressive strains associated with the rocking action can be maintained. The hysteretic response of jointed system is shown in Figure 1b. A key advantage of this type of response is the self-centering nature after each displacement cycle and at the end of a seismic event. Residual displacements are essentially eliminated through the use of the jointed concept. The amount of energy dissipated through one displacement cycle is clearly reduced with the jointed system, but this reduction is not expected to create significant problems in terms of seismic performance.

Both emulative and jointed systems are expected to provide a stable means to dissipate seismic energy during an earthquake. The differences between these two types of systems relate to an important topic in seismic engineering, societal expectations. While both systems are expected to be able to provide satisfactory response from a collapse prevention point of view, jointed systems are expected to do so with significantly less damage. Less damage and residual displacements lead to less public impact as bridge closures can likely be averted. A tradeoff exists between each system, but jointed systems appear to be a superior means to provide seismic resistance.



a) Emulative Connections b) Jointed Connections

Figure 1. Hysteretic Behavior of Precast Systems[6]

INDUSTRY SURVEY AND STATE-OF-PRACTICE

A comprehensive survey of industry professionals was conducted as a preliminary step in NCHRP 12-74 in order to gain an understanding of the concerns of these individuals and to establish the current state-of-practice of precast bent caps.

INDUSTRY SURVEY

Bridge designers and department of transportation officials had similar concerns. Uncertainty regarding how the precast connections would behave had led to minimal use of precast bent caps in regions of high seismicity. The misrepresentation of this connection behavior can lead to gross errors in the anticipated response. Some designers who have previously designed precast bent caps for seismic applications have stated they are unsure of how the system would behave during an earthquake.

Fabricators have stated that the seismic demands placed on a bent cap will likely lead to members which are difficult to fabricate. Most past uses of precast bent caps were in regions with little to no seismic consideration with fabrication not being a significant concern. It is anticipated that the increase in congestion may also lead to increases in cost due to difficulties in fabrication. Some fabricators said that the use of prestressing offers an excellent means to reduce the congestion and provide a member which is simpler to fabricate. With most precast yards already setup for prestressing, this would not be a difficult operation to implement. Fabricators have also stated that shipping these large, heavy bent caps may pose significant problems. Bent caps, unlike conventional girders, apply very large loads over a relatively small distance. This loading configuration can potentially restrict certain transportation routes as they may overload existing structures. Also, very heavy bent caps may necessitate the use of larger equipment on site for handling purposes, subsequently increasing costs. Bent caps should ideally be sized such that the pick weight for the bent cap is no more than that of the heaviest girder.

Most on-site concerns relate to the tolerances which can be provided by a precast bent cap system. Prior projects using precast bent caps afforded contractors only minimal tolerances for the placement of these members. While these projects were completed successfully, special consideration was needed from many aspects. It is more desirable to stay in line with current construction practices and provide tolerances which can be met with little to no special attention.

PRIOR IMPLEMENTATION

A review of past construction projects have yielded almost seventy projects employing precast bent caps. These projects were found in 23 states, Puerto Rico, New Zealand, Europe, Indonesia, and Saudi Arabia. The majority of past projects were found to be in regions of low-to-no seismicity; however, some projects were located in regions with high seismic demand. Many of the details, especially for high seismic applications, relied heavily on in situ casting.

Table 1 provides a summary of the various connection details identified from previous applications. Cap pocket details were used the most of all other connection types; however, there was significant variation among individual cap pocket details. A detail which has become more popular in recent times is the grouted duct connection. This stems from the validation of their use for non-seismic applications through Texas Department of Transportation Project 1748[7]. In this detail, corrugated ducts are cast into the bent cap to accept reinforcement which extends from the column. Mislinski et al. investigated the use of grouted duct connections for high seismic applications through tension-cyclic testing of rebar grouted in corrugated ducts[8]. These results indicate that acceptable behavior can be achieved. Properly designed grouted duct and cap pocket connections are expected to provide behavior similar to cast-in-place. A more in depth

Table 1 Summary of Precast Bent Cap Connection Use

Non-integral Bent Cap Systems	**# of Details**
Grouted Duct Connection	7
Bolted Connection	11
Grouted Sleeve Coupler Connection	4
Cap Pocket Connection	35
Welded Connection	6
Partially Precast Connection	4
Subtotal	*67*
Integral Bent Cap Systems	
Cap Pocket Connection	1
Partially Precast Connection	1
Subtotal	*2*
TOTAL	**69**

review of prior implementation of precast bent caps is provided by Tobolski et al.[9].

CONNECTION CONCEPTS

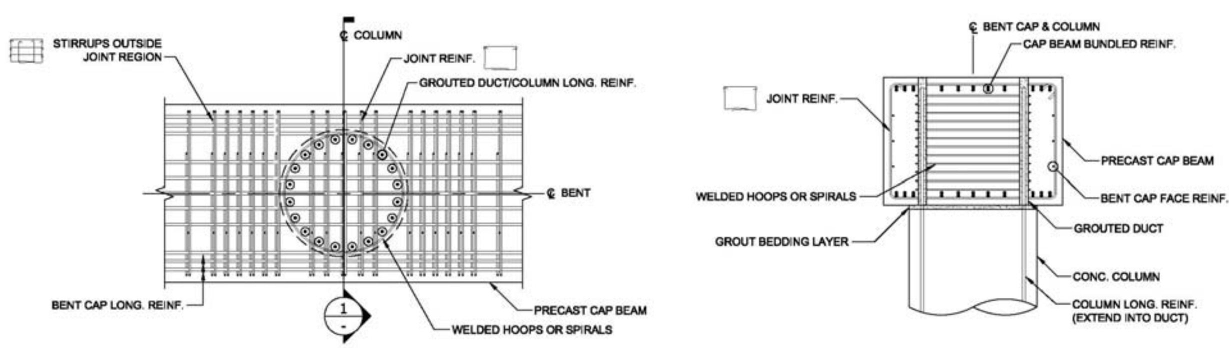
A variety of connection details were developed as a part of this study. Based on a review of expected seismic performance, durability, constructability, and cost, the most promising details were selected for further study. This section provides an overview of the concepts which have been selected.

GROUTED DUCT

The grouted duct connection detail consists of corrugated ducts which are cast into the bent cap to accept longitudinal column reinforcement (Figure 2). Once the bent cap is in place these ducts are grouted to allow for force transfer between the bent cap and column. This detail has been used on a variety of prior projects and their performance for non-seismic applications was recently validated through a Texas DOT research project[7]. Limited ductility grouted duct bent caps are believed to be immediately implementable if designed based on the design guidelines created through the Texas DOT project. Full ductility connections will be validated in the current research program.

Seismic demands generated by column overstrength considerations are expected to necessitate a large quantity of reinforcement in the bent cap. With many high seismic bent caps already congested, the addition of oversized ducts will create members which may be difficult to construct. Based on past experience, minimum acceptable tolerances should be around +/- 1”. Thus, No. 11 reinforcement in the column would lead to duct diameters in of 3.5”. Prestressing of the bent cap is expected to provide an acceptable means to reduce congestion.

Based on review of this connection detail, the seismic behavior is expected to be similar to that of a cast-in-place system. The Texas DOT research project highlighted the importance of using good quality, high strength grout in the ducts. Premature failure was observed when grout quality was poor. Ductile response may not be achieved if the grouted duct connection is not able to resist the required force demands.



a) Plan b) Section

Figure 2. Grouted Duct Connection Concept

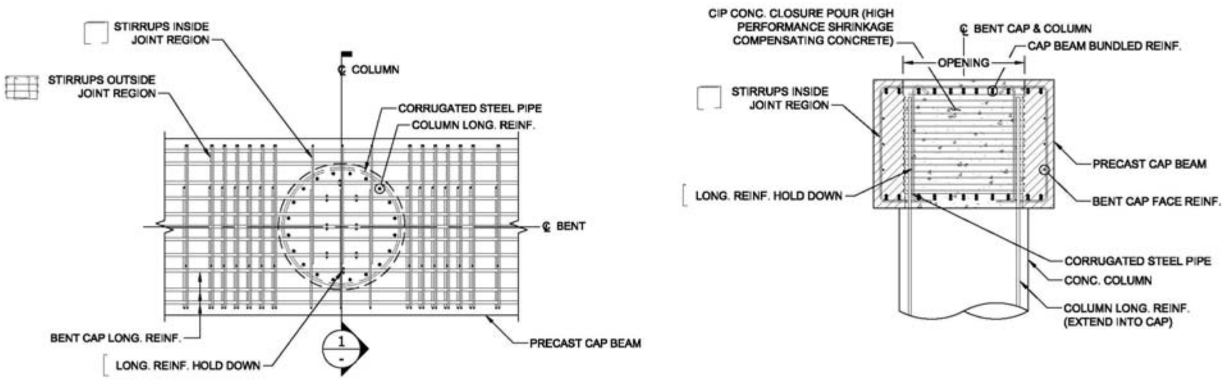


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Figure 3. Cap Pocket Connection Concept

CAP POCKET

The cap pocket connection concept proposed uses a large corrugated steel pipe to form a void in the bent cap as shown in Figure 3. In this detail, the corrugated duct serves as a stay-in-place form as well as providing joint shear reinforcement. Larger tolerances are expected with this detail as column reinforcement only needs to pass between bent cap longitudinal reinforcement and minimal transverse reinforcement for crack control.

This detail is intended to emulate cast-in-place performance, but the actual behavior of such a detail is not clear. Of interest is the effect of the pipe thickness on stress flow in the joint region. Analytical efforts are aimed at determining this effect and will be useful in the development of code requirements. Experimental efforts will investigate the lateral force resisting behavior of both a full ductility and a limited ductility detail.

JOINTED

Two jointed details have been selected for further study through Project 12-74. The first detail represents a conventional jointed system with a solid concrete column and a combination of unbonded post-tensioning and bonded mild reinforcement. Ducts will be cast into the precast cap much like in the grouted duct connection to bond the mild reinforcement. Figure 4 shows the conventional jointed detail. Unbonded post-tensioning is placed in the center of the column in order limit the potential for yielding the reinforcement. It is anticipated that the bent cap will also be post-tensioned in order to enhance the behavior of the bent cap and to reduce any congestion in the bent cap. Special attention must be given to detailing the column ends as they are expected to undergo large compressive strains from the rocking response.

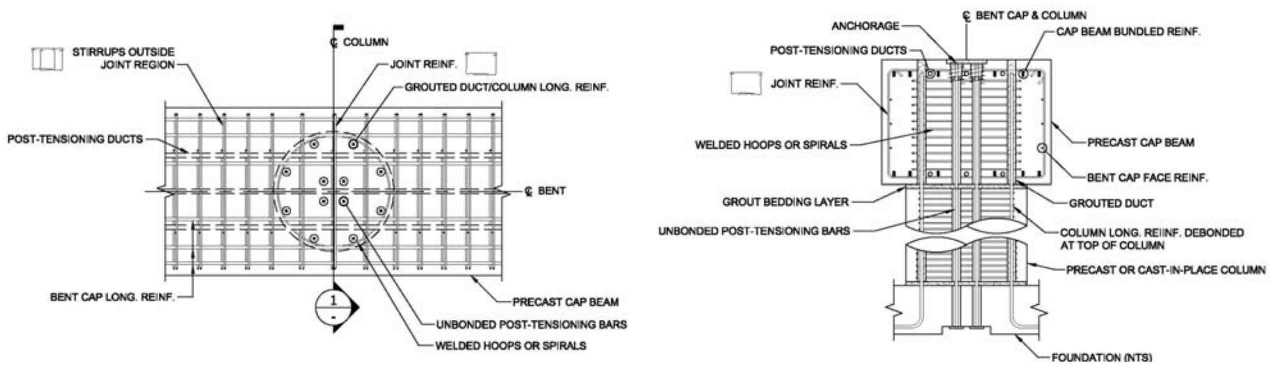

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Figure 4. Traditional Jointed Concept

The second detail uses a dual-shell concrete filled steel column as shown in Figure 5. The details of the actual bent cap are the same as the first detail, with the only difference being the column. No longitudinal reinforcement will be used in the bent cap, other than for energy dissipation at the column ends. Both steel pipes are designed to act as the longitudinal and transverse reinforcement for the column. Appropriate force transfer mechanisms must be investigated to ensure the concrete and steel act together. One major aim of this detail is to provide a light and simple to handle column such that these columns can be precast, furthering the goal of accelerated construction. Both details are expected to provide superior seismic resistance in a constructible manner. It is expected that the first projects using these details will be more expensive as they have never been used before, but over time the cost is expected to be reasonable.

FUTURE ACTIVITIES

Remaining work to be conducted under Project 12-74 includes 2- and 3-dimensional strut-and-tie modeling, finite element analyses, non-linear time-history analyses, component testing, a system test, and development of specifications. This section describes the activities to be conducted in some detail.

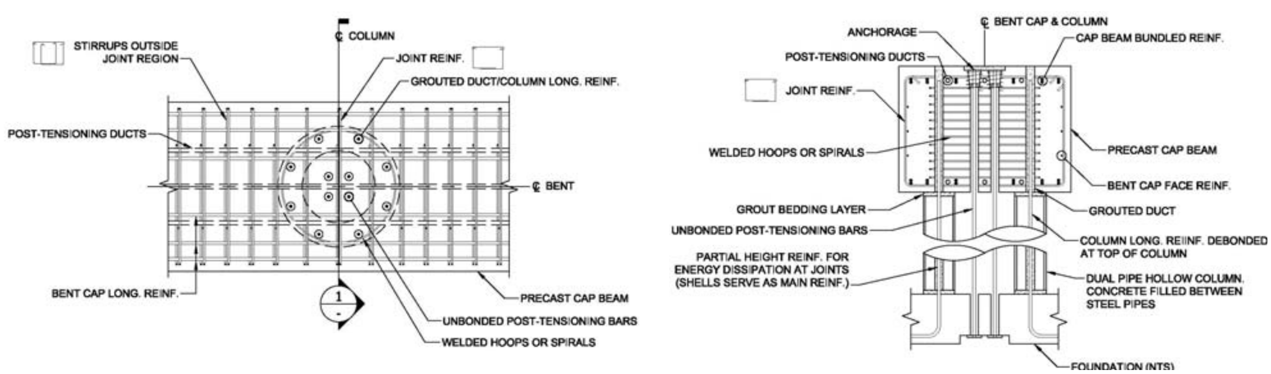

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Figure 5. Dual-Shell Jointed Concept

STRUT-AND-TIE MODELING

A rational means to design joint regions in a concrete bent cap is through the use of strut-and-tie models. For each connection detail, models will be developed which are intended to appropriately characterize force transfer mechanisms in the cap. It is expected that strut-and-tie models developed for emulative connections will be similar to those which have been previously developed for cast-in-place systems. New models are intended to be developed for jointed and integral systems as well. While the use of actual strut-and-tie models may not be used for design, they may be employed in developing design equations for use by design engineers such as is done in the California Department of Transportation Seismic Design Criteria[10]. In this case, simplified equations are developed based on the assumed force transfer mechanism and reinforcement is designed accordingly. Initial efforts are currently underway in developing these models that are to be validated through component testing.

FINITE ELEMENT ANALYSES

Certain connection details have features which may affect the behavior in unknown ways, such as pipe thickness. For these details, finite element analyses will be performed in an attempt to understand these effects. The behavior of the cap pocket detail is expected to be influenced by the thickness of the pipe used. This effect is not anticipated to be significant, but gaining an understanding is considered important for codification purposes. The dual-shell steel pipe jointed detail utilizes arching action in the inner steel pipe to provide confinement of concrete. Pipe thickness is essential to ensure the buckling of the pipe does not occur. Issues such as these will be investigated through the use of complex finite element models.

NON-LINEAR TIME-HISTORY ANALYSES

Based on results from other analytical and experiment efforts, reasonable force-deformation relationships will be developed for each detail. These will then be used to perform non-linear time-history analyses in order to develop appropriate capacity-demand ratios for use in developing design recommendations. It is anticipated that a minimum of two bridges will be considered which will be designed according to AASHTO LRFD specifications with appropriate modifications based on NCRHP Project 20-07 Task 193 results. Each structure will be designed for low, moderate, and high seismicity and subjected to a series of scaled ground motion records in order to estimate the structural response under a variety of excitations. It is expected that these records will be scaled to a variety of demand levels to investigate no only ultimate performance, but also more common seismic events in an attempt to quantify damage potential.

COMPONENT TESTS

A series of component tests will be conducted in order to determine the lateral response of each connection detail. These tests are aimed at understanding the transverse response of a non-integral bent cap. Specimens will be designed based on a prototype structure which is representative of a common highway overcrossing found throughout the United States. The specimens tested are scaled to approximately 40% that found in the prototype structure. Quasi-static loading will be applied to the members in increasing ductility levels. Results from these tests will serve to provide basic force-deformation relationship for each of the details. Analytical models will also be validated based on these results. One goal of component testing is to validate that assumption that emulative behavior is achieved for those details where this is the aim. Jointed details will have a much different response, and these tests will help to develop appropriate design recommendations for jointed systems.

SYSTEM TEST

Component tests alone are not expected to provide enough understanding of the behavior of an integral system. Consequently, a large-scale system test will be performed on an integral detail of choice. Testing of an entire system will aid in understanding the interaction between the bent cap, columns, and girders. Results from the component testing will be used in developing the system test. It is anticipated that a multi-column bent will be tested with four concrete girders. Loading will be actively controlled through the use of 10 hydraulic actuators and will be bi-directional. Results of the time-history analyses will be used in developing this loading protocol. System testing will promote confidence in the actual behavior of the precast, integral bent cap of interest.

CONCLUSIONS

Uncertainties associated with the seismic behavior and lack of design guidance has resulted in the limited use of precast bent caps in regions prone to strong ground motion. While the behavior is not fully understood, these systems have been used in a variety of seismic applications throughout the world. NCHRP Project 12-74 is currently underway with the goal of developing validated design and construction specifications to promote the widespread use of precast bent caps in all seismic regions of the United States. In order to develop these specifications, a series of analytical and experimental efforts are currently being performed. Products developed under Project 12-74 will allow designers to confidently design precast bent caps for seismic applications which are both constructible and economic.

ACKNOWLEDGEMENTS

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