OVERVIEW OF NCHRP RESEARCH

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Abstract

The policies and procedures of the National Cooperative Highway Research Program (NCHRP), an applied research program, are discussed. A brief overview of recent and ongoing research is provided. Topics discussed include redundancy in bridge superstructures and substructures, extreme event load combinations, blast resistance of concrete bridge columns, seismic design provisions for retaining walls, buried structures, slopes, and embankments, and integral pier caps.

Introduction

The National Cooperative Highway Research Program (NCHRP) was created in 1962 to manage a program of research on highway planning, design, construction, operations, and maintenance. NCHRP is sponsored by the American Association of State Highway and Transportation Officials (AASHTO) in cooperation with the Federal Highway Administration (FHWA) and is administered by the Cooperative Research Programs (CRP) Division of the Transportation Research Board (TRB). The AASHTO member states voluntarily contribute a fixed percentage of their federal highway construction funds to the NCHRP. The states benefit from the entire research effort while only contributing a portion of the cost.

Only the states, AASHTO Committees, and FHWA are eligible to submit problem statements for funding under the NCHRP program. From the problems received each year the AASHTO Standing Committee on Research (SCOR) recommends those to program. The SCOR recommendations require a 2/3 majority approval by the member states.

A unique aspect of the NCHRP process is its reliance on advisory panels. Each project is assigned to a TRB-appointed panel of experienced practitioners and research specialists. Although most panel members are employed by AASHTO Member Departments, panels also may includes individuals from universities and the private sector. These panels employ their collective expertise to guide the research agencies in developing authoritative, practical products for use by AASHTO and others. Project panels have four primary responsibilities: (1) translate the new AASHTO problems into NCHRP requests for proposals with well-defined objectives, (2) select contractors based on evaluation of the proposals received, (3) monitor and guide the research from beginning to end, and (4) review reports and other products for acceptability and accomplishment of the agency's research plan.

Since 1962 NCHRP has issued contracts for more than 1100 projects and more than 300 projects are active today. In the bridges and structures area more than 130 contracts have been started since 1962 with 47 projects active today (current contract

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value exceeds $20,000,000). The current AASHTO LRFD Bridge Design Specifications were developed under NCHRP project 12-33. Since the adoption of these specifications in 1994 nearly all NCHRP bridge and structures research has been directed towards refinement and expansion of that document. Complete details of the NCHRP program may be found at www.trb.org.

Several ongoing or recently completed projects are consistent with the themes of this conference. The topics discussed below include redundancy in bridge superstructures and substructures, extreme event load combinations, blast resistance of concrete bridge columns, seismic design provisions for retaining walls, buried structures, slopes, and embankments, and integral pier caps.

Redundancy

The AASHTO LRFD Bridge Design Specifications define redundancy as "The quality of a bridge that enables it to perform its design function in a damaged state." It is not clear from this definition how to evaluate redundancy and the specifications provide little further guidance. Michel Ghosn and Fred Moses developed a process for quantifying redundancy in bridge superstructures (Ghosn 1998). Liu later collaborated with Ghosn and Moses to extend the process to substructures (Liu 2001).

Ghosn took a systems approach to quantifying redundancy. He argues that a bridge is safe if it 1) provides a reasonable safety against first member failure, 2) provides an adequate level of safety before it reaches its ultimate limit state 3) does not deform excessively under expected loads, and 4) is able to carry some traffic loads after damage to or loss of a member. Accordingly, 4 limit states are defined as:

- Member failure - a check of individual members using elastic analysis
- Ultimate - the capacity of the bridge system or the formation of a collapse mechanism (nonlinear analysis)
- Functionality – capacity of the structure to resist a main member live load displacement of specified magnitude (nonlinear analysis)
- Damaged Condition – ultimate capacity after removal of one-main load carrying component. (nonlinear analysis).

The capacity of the bridge to carry live load before the limit states are reached is related to the 'live load margin' defined as the difference between bridge capacity and dead load effect. The live load margin is expressed as the multiplier of two HS-20 trucks, referred to as the load factor. Thus, application of the limit states establishes 4 load factors $LF_{1,}$ LFu, LF_f, LF_d for the member, ultimate, functionality, and damaged states, respectively. Consistent with the LRFD definition of redundancy, system reserve ratios, R, serve to quantify redundancy. These ratios are defined for the ultimate, functionality, and damage states as the ratio of the load factor for the respective limit state to the member load factor.

The redundancy check can be implemented by direct calculation or through calibrated 'system factors' to be used in the design check equation. For the direct calculation approach a program capable of performing a nonlinear incremental analysis is required. A 10 step process for accomplishing this analysis is detailed by Ghosn (1998). System factors, ϕ_s for use in the LRFD design check equation $\phi_s \phi R_n \geq \sum \gamma_i Q_i$ are calculated for superstructures from $\phi_s = \min\left(\frac{R_u}{1.30}, \frac{R_f}{1.10}, \frac{R_d}{0.50}\right)$ with $0.80 \leq \phi_s \leq 1.20$.

When a non-linear analysis is not possible or practical, representative system factor values for bending of members of multi-girder systems were recommended by Liu. Typical values for superstructures are shown in Table 1.

Table 1 System Factors for Superstructures

System/member type	ϕ_{su}
Two-girder bridges	0.85
Three-girder bridges with spacing ≤1.8m	0.85
Four-girder bridges with spacing ≤1.2m	0.85
Other girder bridges with spacing ≤1.2m	1.00
All girder bridges with spacing ≤1.8m	1.00
All girder bridges with spacing ≤2.4m	1.00
All girder bridges with spacing ≤3.0m	0.95
All girder bridges with spacing ≤3.6m	0.90
All girder bridges with spacing >3.6m	0.85

Extreme Events

Michel Ghosn and Fred Moses also studied combinations of extreme events under NCHRP Project 12-48 (Ghosn 2004). The magnitude and consequences of extreme events such as vessel collisions, scour due to flooding, hurricane winds, and earthquakes often govern the design of highway bridges. If the simultaneous occurrence of these events is considered, the resulting loading condition may dominate the design. This superpositioning of extreme load values frequently increases construction costs unnecessarily because a simultaneous occurrence of two or more extreme events is unlikely. The reduced probability of simultaneous occurrence for each load combination can be determined using statistical procedures.

The *AASHTO LRFD Bridge Design Specifications* developed under NCHRP Project 12-33 covered mostly the basic design combinations with dead load and live load. Extreme load combinations were not considered in the LRFD calibration because of the lack of readily available data concerning the correlation of extreme events. Nevertheless, a probability-based approach to bridge design for extreme events can be accomplished through incorporation of state-of-the-art reliability methodologies.

It is not possible to construct bridges to resist simultaneous occurrence of extreme events or to install countermeasures or protection systems at all existing bridges to ensure absolute invulnerability from extreme events and their combinations. Nevertheless, the need to ensure public safety and minimize adverse effects resulting from bridge collapse requires the best efforts of bridge engineers to improve the state of practice for designing and maintaining bridges to resist extreme loads with uniform reliability.

The objective of this research was to develop a design procedure for the application of extreme event loads and extreme event loading combinations to highway bridges. This objective has been achieved with a recommended design procedure consistent with the uniform reliability methodologies and philosophy included in the *AASHTO LRFD Bridge Design Specifications*. Four new extreme event load combinations are recommended to maintain a consistent level of safety against failure caused by scour combined with live load, wind load, vessel collision, and earthquake, respectively.

The recommended revisions to the AASHTO LRFD Specifications addresses extreme loads by ensuring that the factored member resistances are greater than the maximum load effects obtained from the following combinations:

Strength I Limit State:		1.25 DC + 1.75 LL	
Strength III Limit State:		1.25 DC + 1.40 WS	
Strength V Limit State:		1.25 DC + 1.00 LL + 1.20 WS + 1.20 WL	
Extreme Event I:		1.25 DC + 0.25 LL + 1.00 EQ	
Extreme Event II:		1.25 DC + 0.25 LL + 1.00 CV	
	Or	1.25 DC + 0.30 WS +1.00 CV	
Extreme Event III:		1.25 DC	; 2.00 SC
	Or	1.25 DC + 1.75 LL	; 1.80 SC
Extreme Event IV:		1.25 DC + 1.40 WS	; 0.70 SC
Extreme Event V:		1.25 DC + 1.00 CV	; 0.60 SC
Extreme Event VI:		1.25 DC + 1.00 EQ	; 0.25 SC

In the equations given above, DC represents the dead load effect, LL is the live load effect, WS is the wind load effect on the structure, WL is the wind load acting on the live load, EQ is the earthquake forces, CV is the vessel collision load, and SC represents the design scour depth. The dead load factor of 1.25 would be changed to 0.9 if the dead load counteracts the effects of the other loads.

Blast Resistance

The blast resistance of highway bridges is being studied at the University of Texas Austin under the direction of Eric Williamson in NCHRP Project 12-72. The objective of this project is to develop design guidance for improving the structural performance and resistance to explosive effects of new and existing bridges. There is a need to protect bridges from intentional or accidental explosions. The impacts of these loads on buildings and military structures have been studied for many years, but design for resistance to explosive effects is a new area for bridge engineers.

The experimental plan for the project includes blast testing of non-responding square and round columns. A preliminary series of tests on 1:6 scale specimens has been completed. The objective of these tests was to determine the pressure-time history on square and round columns. The test specimens were fabricated from thick-walled pipe and steel plate. Typical results for a square column are shown in Figures 1 and 2. Although there is a significant difference between the measured and predicted peak pressures, the measured and predicted impulse, which strongly influences column response, compare well.

The second test series will include larger scale column shear/flexure and local damage tests. The analytical program focuses on investigations of reinforced concrete piers and prestressed concrete girder superstructures. Piers are emphasized because they are integral to the structural integrity of all bridge types. In addition, test data from building columns can not be extrapolated because of the different aspect ratios and because of the difficulty in achieving increased standoff distances in bridges. Prestressed concrete girders are emphasized because they represent a large proportion of the U.S. bridge inventory and there is limited knowledge about how they respond to blast loads.

The contractor has also been asked to develop a set of guidelines for selecting analysis techniques to use in designing for explosive effects. The emphasis of this effort is to identify simplified computer modeling methods that bridge engineers can use to predict component behavior under blast loading. The researchers have investigated single degree-of-freedom (SDOF) and distributed mass modal analysis (DMMA) methods. Several researchers have speculated that because bridge components such as girders and tall piers have long spans, the inclusion of higher-order modes in the DMMA method might produce more accurate predictions of response than SDOF models for bridge components subjected to blast loads.

Results from SDOF and DMMA models were compared with those from plane-stress and beam element finite element analysis (FEA) models. Idealized blast loads were applied to long-span girders with lengths ranging from 60 ft to 160 ft. All models produced very similar results when the member response was assumed to remain elastic. For girders responding in their plastic range, however, the DMMA method yielded highly inaccurate results, while the SDOF method computed responses that differed from the detailed FEA models by less than 10% in most cases.

In addition, the contractor is developing a user-friendly software package that can be used to analyze the response of bridge components subjected to blast loads. This will be a Windows-based program. The research team has selected Visual Basic 2005 to construct a graphical user interface (GUI) and FORTRAN to implement the SDOF analyses using Newmark's method. The work is continuing on incorporating additional capabilities and features that are needed to accurately analyze bridge components subjected to blast. Features planned for inclusion are:

1. account for the effects of localized damage (i.e., spall and breach);
2. a member resistance function that includes membrane action, arching action, and strain-hardening;

3. material strain-rate effects as a function of time;
4. changes in loading and load-mass factors as a function of both time and position;
5. allowing users to import load-time histories;

<u>Seismic Design</u>

A comprehensive load and resistance factor design (LRFD) specification for the seismic design of highway bridges was recently adopted by AASHTO. This work, which is largely based on the recommendations from NCHRP Project 12-49, which was performed by the Applied Technology Council and the Multidisciplinary Center for Earthquake Engineering Research, was undertaken so that seismic design of bridges will reflect the latest bridge design philosophies for achieving high levels of seismic performance. The specifications recently adopted by AASHTO are limited to highway bridges and components that are directly attached to them, such as abutments and wing walls. The specifications do not address new or improved analytical methods or seismic design provisions for retaining walls, buried structures, slopes, or embankments. For example, a short-coming in retaining wall seismic design is that the method currently used to estimate seismic earth pressures is unreliable for large ground motions. There are also deficiencies and gaps in coverage in the current seismic design provisions for buried structures, slopes, and embankments.

It is important to develop analysis and design methodologies for these geotechnical structures based on sound soil-structure interaction principals. Specifications based on these methodologies must be compatible with the new LRFD seismic provisions for highway bridges being developed by AASHTO.

The objective of NCHRP project 12-70 is to develop analytical methods and recommended LRFD specifications for the seismic design of retaining walls, buried structures, slopes, and embankments. This work, which is being performed by CH2MHill under the direction of Don Anderson and with the assistance of Geoff Martin and Po Lam, is nearing completion.

The specifications and commentaries are presented in three sections:

- Retaining Walls — This section provides proposed specifications and commentaries for six types of retaining walls: (1) rigid gravity and semi-gravity (conventional) walls, (2) nongravity cantilever walls, (3) anchored walls, (4) mechanically stabilized earth (MSE) walls, (5) prefabricated modular walls, and (6) soil nail walls. With the exception of soil nail walls, each of these wall types are covered within the current AASHTO *LRFD Bridge Design Specifications.*
- Slopes and Embankments — This section provides proposed specifications and commentaries for the seismic design of slopes and embankments. The specifications cover natural slopes and engineered fills. A methodology for addressing sites with liquefaction potential is included in the specifications. Current AASHTO *LRFD Bridge Design Specifications* do not provide specific guidance on the methods used to evaluate the stability of slopes under gravity

and live loads. In this case the specifications and commentaries use the "standard of geotechnical practice" as the starting point for design.

- Buried Structures — This section covers the seismic design of culverts and drainage pipes. The discussion focused on the design for transient ground displacements (TGD) and included mention of the requirements for design for permanent ground displacements (PGD). Generally, the ability of the culvert or drainage pipe to withstand PGD depends on the amount of permanent ground movement which occurs during the seismic event. Procedures given in Section Y provided a means for estimating these displacements. Culverts and drainage pipes will generally move with the ground; therefore, movement of more than a few inches to a foot will often damage the pipe or culvert.

An appendix presenting charts for seismic active and passive earth pressure coefficients that included the contributions from cohesion and an appendix summarizing the design of nongravity cantilever walls using a beam-column displacement method also are included.

Integral Pier Caps

An integral connection provides some degree of continuity between the substructure and adjacent superstructure spans. Applications of integral connections include:

- Simple-span girders made integral with the concrete substructure to provide continuity for live load and reduce fabrication and erection costs,
- Continuous girders made integral with the concrete substructure for enhanced seismic performance,
- Continuous girders made integral with the concrete substructure to achieve increased clearance.

Although integral connections are common in concrete bridges, steel I-shaped or box girder highway bridges have traditionally been designed as two separate systems: the substructure and the superstructure. As such, the connection between the two has typically relied on a system composed of anchor bolts and bearings. Although such systems simplify the design process by uncoupling the computations related to the sub- and superstructures, there are cost and performance disadvantages.

A composite steel girder bridge superstructure weighs substantially less than a concrete superstructure. This reduction of mass in the superstructure reduces the seismic susceptibility of bridge structures. Steel superstructures placed on top of large concrete drop bent caps or hammerhead piers can result in unnecessary mass. Integral construction eliminates this mass, increases clearance, and provides improved aesthetics.

Concrete bridge superstructures are often constructed integral with the substructure. Thus, the entire structure is treated as one system to resist loads, and lateral loads are distributed to adjacent piers resulting in more economical foundations.

Similar economies are possible in steel bridges through integrally connecting steel superstructures to concrete substructures.

The objective of NCHRP project 12-54 was to develop recommended details, design methodologies, and specifications for integral connections of steel bridges. The work was performed by Modjeski & Masters and Iowa State University (Wassef, et al. 2004). The study concentrated on a system consisting of a steel-box beam pier cap connected integrally to a steel I-girder superstructure and a reinforced concrete single-column pier. The integral connection between the column and the pier cap was accomplished by extending the column longitudinal reinforcement through holes in the bottom flange of the pier cap into the pier cap compartment directly above the column as shown in Figure 3. This compartment is then filled with concrete which transfers the load from the pier cap to the column reinforcement.

Grillage models were analyzed to design a two-span bridge. Two, one-third scale, test-specimens were constructed and tested. The results indicated that the tested connection is capable of developing the column plastic hinging and of providing adequate ductility. The experimental force displacement response of one specimen is shown in Figure 4.

A design methodology, connection details, and design and construction specifications for precast bent cap systems under seismic loading are being developed in ongoing NCHRP Project 12-74. The work is underway (2007) at the University of California, San Diego and California State University Sacramento. Precast bent cap systems are of increasing utility in highway construction. Precasting moves concrete forming, pouring, and curing operations out of the work zone, making bridge construction safer and more environmentally friendly, and it removes bent cap construction from the critical path. Precasting also improves quality and durability because the work is performed in a more controlled environment.

Successful use of precast bent caps relies on proper design, constructability, and performance of the connections. Early uses of precast bent caps were limited to applications where minimal moment and shear transfer were required at connections. In seismic regions, provisions normally must be made to transfer greater forces through connections.

Both emulative and jointed connection details will be tested. Emulative connections perform similar to CIP connections, dissipate energy through system yield, and have residual displacement. Jointed connections use unbonded prestressing strands, provide a larger displacement capacity and return to zero displacement following an earthquake. Although there is less permanent damage than with emulative or CIP connections, jointed connections dissipate less energy.

Conclusions

The NCHRP program has been invaluable to AASHTO in providing implementable solutions to highway transportation problems. In the bridge and structures area the program has been of key importance to developing and refining bridge design standards.

References

1. AASHTO, 2006. *LRFD Bridge Design Specifications*, American Association of State Highway and Transportation Officials, Washington, D.C.
2. Ghosn, M. and Moses, F., *NCHRP Report* Redundancy in Highway Bridge Superstructures," Transportation Research Board, Washington, D.C. (1998)
3. Ghosn, M., Moses, F, and Wang, J., *NCHRP Report 489,* "Design of Highway Bridges for Extreme Events", Transportation Research Board, Washington, D.C. (2004)
4. Liu, W. D., Neuenhoffer, A., Ghosn, M., and Moses, F., *NCHRP Report 458*, "Redundancy in Highway Bridge Substructures", Transportation Research Board, Washington, D.C. (2001)
5. Wassef, W.G., et al., *NCHRP Report 527,* "Integral Steel Box-Beam Pier Caps", Transportation Research Board, Washington, D.C. (2004)

Figures

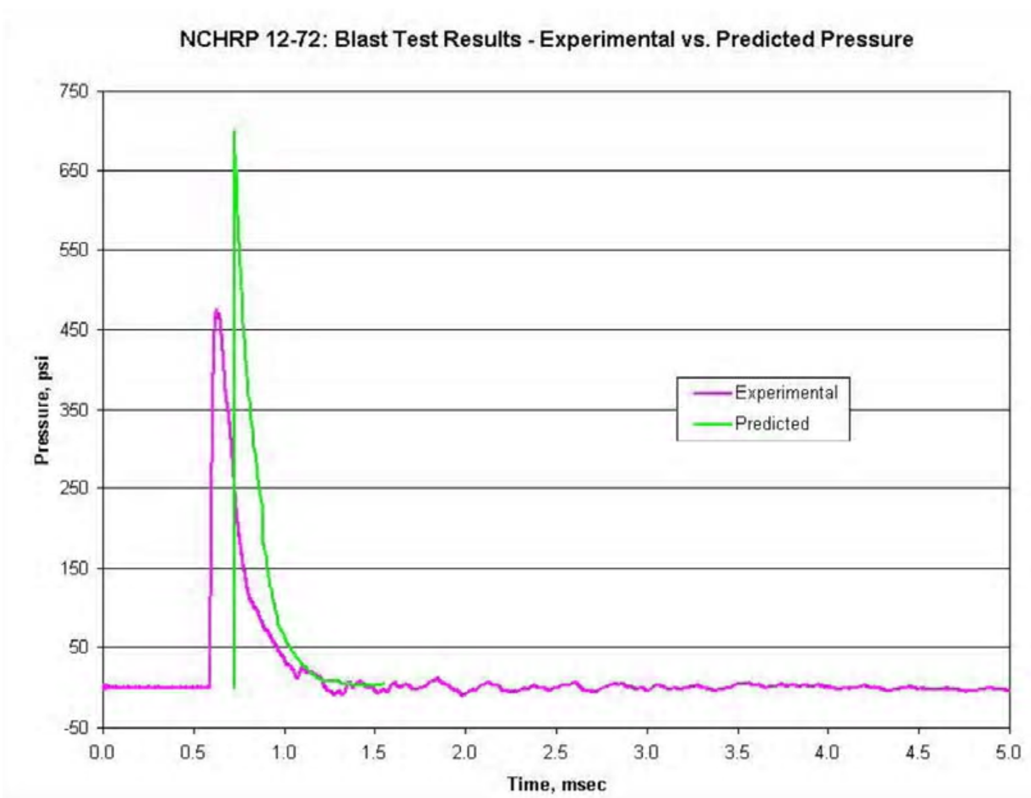

Figure 1 NCHRP 12-72: Experimental vs. Predicted Pressures

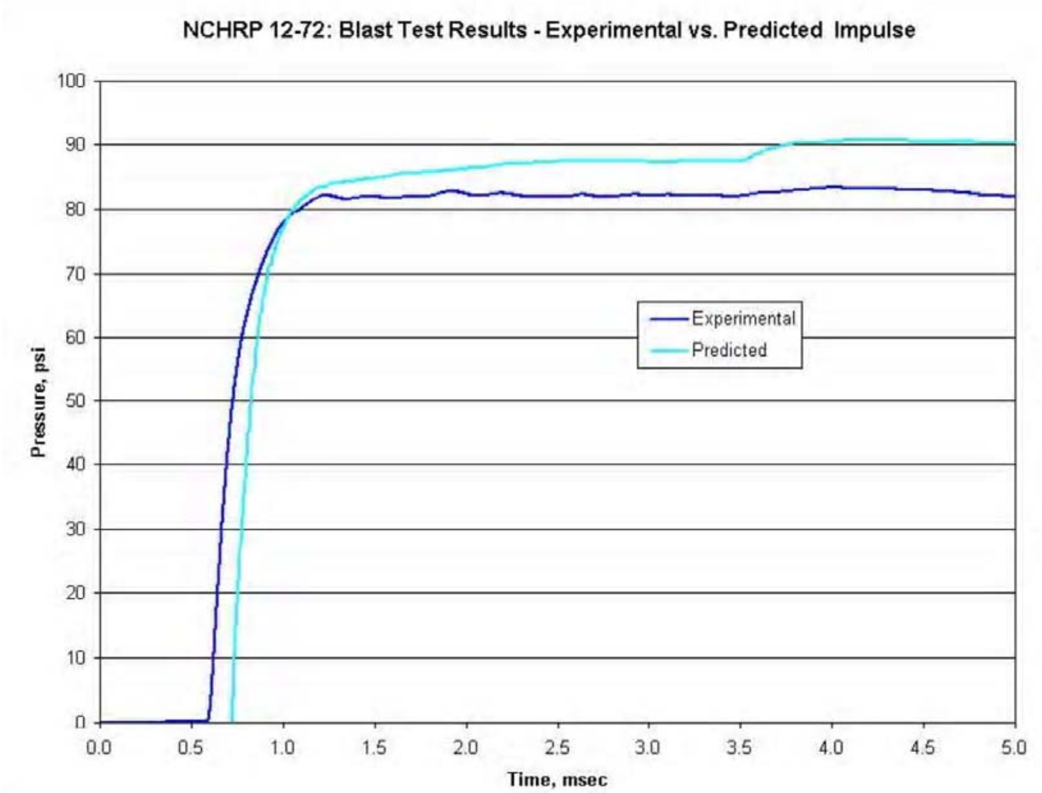

Figure 2 NCHRP 12-72: Experimental vs. Predicted Impulse

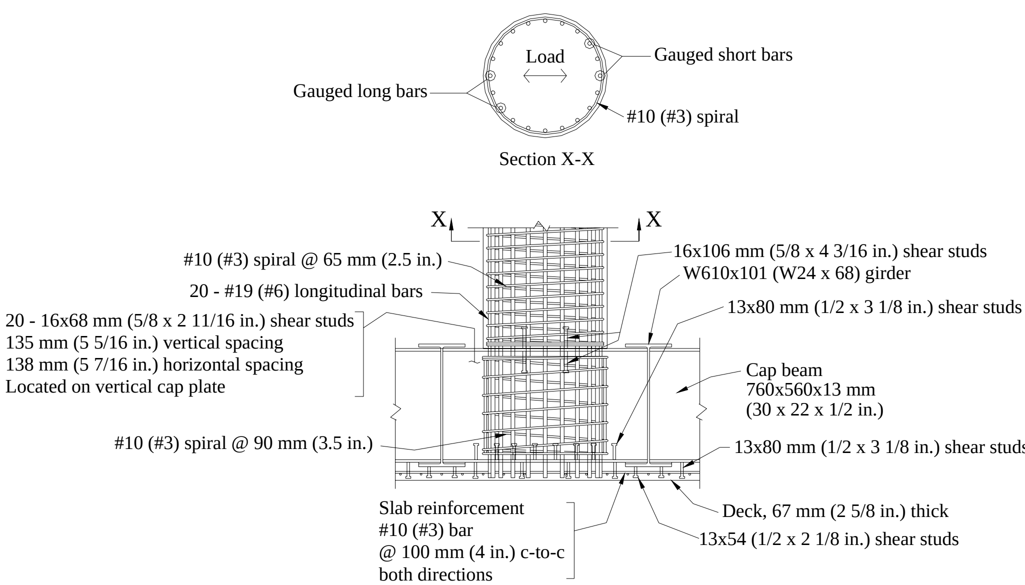

Figure 3 NCHRP 12-54: Column-to-cap beam connection detail

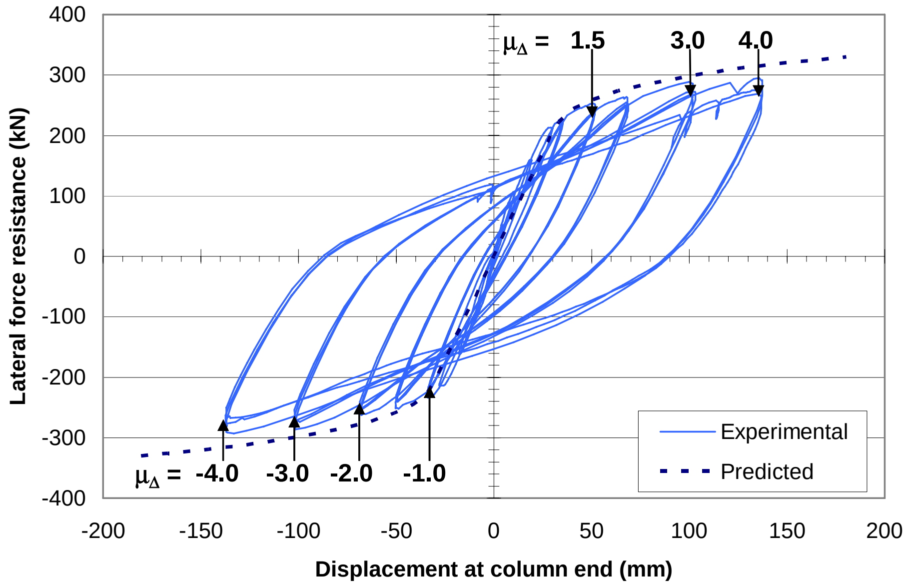

Figure 4 NCHRP 12-54: Column lateral force-displacement response

Emulative vs. Jointed Connections