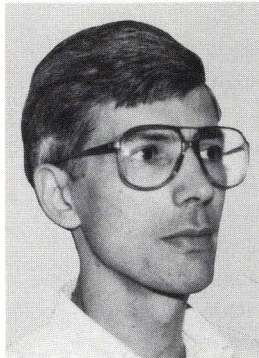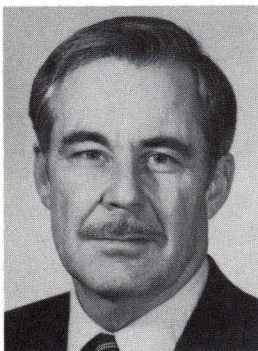# PRESSS Project 1.3: Connection Classification and Evaluation

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This paper describes the studies on connections in precast concrete structures being conducted under the PRESSS Research Program. The goal of the overall program is to develop precast concrete systems suitable for use in seismic environments and to recommend the design and construction methods necessary to achieve them in practice. The connection work described here concerns the classification and evaluation of existing connections for the purpose of selecting the most promising systems for further development, for analysis, and ultimately, for testing.
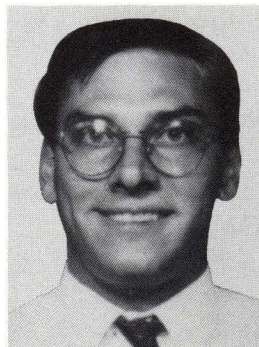
PREcast Structural Seismic Systems (PRESSS) is a coordinated research program being conducted in the United States, in parallel with a similar effort in Japan, to develop seismic design procedures for precast concrete structures. An overview of the program has been provided by Priestley.[1]

Of the five projects funded under Phase 1 of the program, Project 1.3 addresses connections and is the subject of this paper. Project 1.1 (Concept Development) is described by Nakaki and Englekirk in this issue of the PCI JOURNAL[2] (pages 54-61). The issues of system performance and connection details are inextricably intertwined, and, although these two projects are funded separately and are being conducted by different organizations, liaison between the two agencies has been close. The projects are described in separate papers as a matter of formality.

Development of precast concrete for use in seismic regions faces both behavioral and regulatory obstacles. The behavioral ones concern the difficulties in designing precast concrete structures to have suitable structural characteristics to survive earthquakes without either reducing the inherent advantages of precasting, such as product quality and speed of erection, or requiring details that make precasting economically uncompetitive. Much of the development of precast concrete in the United States has occurred in parts of the country such as the East Coast where seismic issues have historically played little or no part in design. The result is that many of the connection details in common use there do not display the toughness and robustness desirable in seismic resistant structures.

The regulatory impediments are closely linked to the behavioral ones. American building codes, and in particular the Uniform Building Code (UBC),[3] do not contain specific seismic design provisions for precast concrete structures. Therefore, such structures must either be designed to satisfy the prescriptive requirements for cast-in-place concrete or they must be shown by experimental evidence and analysis to display strength and toughness equivalent to a reinforced concrete system that does satisfy the requirements.

The first option is often difficult for physical reasons. A hybrid mode, whereby the precast concrete members are joined by regions of site-cast concrete, presents a possible solution and is often referred to as the "emulation" approach, since the precast structure emulates a cast-in-place system. It is popular in Japan and New Zealand, but for reasons of practice is little used in the United States. Demonstrating equivalent toughness is difficult because no criteria are given for doing so, and there is little incentive for a Building Official to develop his own provisions.

It is the purpose of the PRESSS program to address both of these issues by an improved understanding of the structural characteristics of precast concrete, which will lead to better seismic details and to recommenda-tions for seismic design and construction procedures. One of the main areas of interest is the trade-off between design strength and ductility capacity, which is embodied for other materials in the R_w factors in Chapter 23 of the UBC. R_w is essentially the factor by which dynamic loads predicted by elastic analysis are divided in order to arrive at a design load which takes into account inelastic action. A large R_w (e.g., 10) implies a large reduction in force which is permissible only in a very tough, ductile system. In materials such as cast-in-place concrete or steel, the toughness required to justify the UBC R_w factors is guaranteed by the imposition of prescriptive detailing requirements.

PRESSS is overseen by an Executive Committee, on which research and design interests are represented. Separate applications and research committees also exist, which report to the Executive Committee. The Applications Committee includes producers, contractors and designers. The Precast/Prestressed Concrete Institute (PCI) has also formed an Ad Hoc Liaison Committee through which to transmit information to and from the researchers.

PREVIOUS WORK

Many physical tests have been conducted on connections, and they are reviewed in some detail in Reference 4. In addition to publicly available studies, a number of experiments have been carried out in-house by individual producers. Since the conditions of such tests tend to vary widely, it is difficult to assess definitively all the connections that have been tested to date.

The PCI Connections Manual[5] contains descriptions of approximately 100 connections fulfilling many functions, but published test data are available for only a few of them. They are not intended specifically for use in seismic regions, although some might prove suitable. PCI sponsored a test program[6] on a variety of both panel and frame connections selected from the PCI Connections Manual, but only monotonic testing was specified. Even so, many specimens were subjected to up to three cycles of loading and so the results provide a useful experimental basis. None demonstrated desirable seismic behavior in their as-tested form.

Experiments on frame components have been conducted by French,[7] who has tested a number of beam-to-column specimens incorporating prestressed and nonprestressed reinforcement and including details designed to allow inelastic action in the joint region or to force it elsewhere. All dissipated some energy and showed promise, and no one connection proved vastly superior to all others. A testing program is currently under way at the National Institute of Standards and Technology (NIST)[8] in which prestressed beam-to-column specimens are being subjected to reversed cyclic loads. Extensive work has also been carried out in New Zealand,[9] although most of it has concentrated on the emulation approach.

In Japan, many of the large construction companies are at present involved in research on precast concrete because of the acute shortage of construction labor there. Again, most of the work revolves around the emulation approach. A number of other tests have been conducted in the United States and elsewhere. It is apparent that some systems that have been tested but not built would not be economical, and that others which have proved economical abroad might not be competitive in the American market. Connections which are both structurally robust and easy to build are rare.

Panel connections intended for seismic resistance have been tested.[6,10] In many cases the connections made by attaching steel plates across the joint failed by pulling the embedded hardware out of the panels. Such behavior makes repair after an earthquake difficult and tends not to provide repeatable cycles of energy dissipation during one. However, friction across a horizontal joint between panels, provided by self-weight aided by prestress as necessary, has been shown to supply such energy dissipation, but good confinement on the compression side of the cantilever wall is needed to avoid premature local crushing failure. Pekau[11] and others have demonstrated

GC02—Top

ELEVATION

SECTION

Plate, Embedded Plate, Angle, Stud, Bottom Horizontal Connection and Vertical Restraint Not Shown, Slab

Connection Classification: Girder-to-Column Connection

Design Elements:
a) Bent-up bars - design element for anchorage in column
b) Plate embedded in column - design element for bending
c) Loose plate - design element for tension (yield)
d) Welds on loose plate - design element for tension
e) Studs in beam - design element for anchorage

Fabrication:
Construct column
- Weld anchorage bars or studs to embedded plates
- Construct column cage with embedded plates in place
Construct beams
- Butt weld reinforcing bars to the angles to lap with the main beam negative reinforcement or cut the reinforcement to the correct length before welding
- Weld studs to embedded angles
- Construct the beam cage
- Position the connection hardware in the beam cage and enclose the studs in horizontal U-bars
- Prepare loose connecting plates

Erection:
- Place beams on corbels or temporary supports and adjust for vertical and horizontal positioning
- Position slab on beams
- Weld the loose connecting plate as indicated
- Fire proof and protect connection from corrosion

Variations on Design:
- Use continuous connector bars from one embedded plate to the other in the column

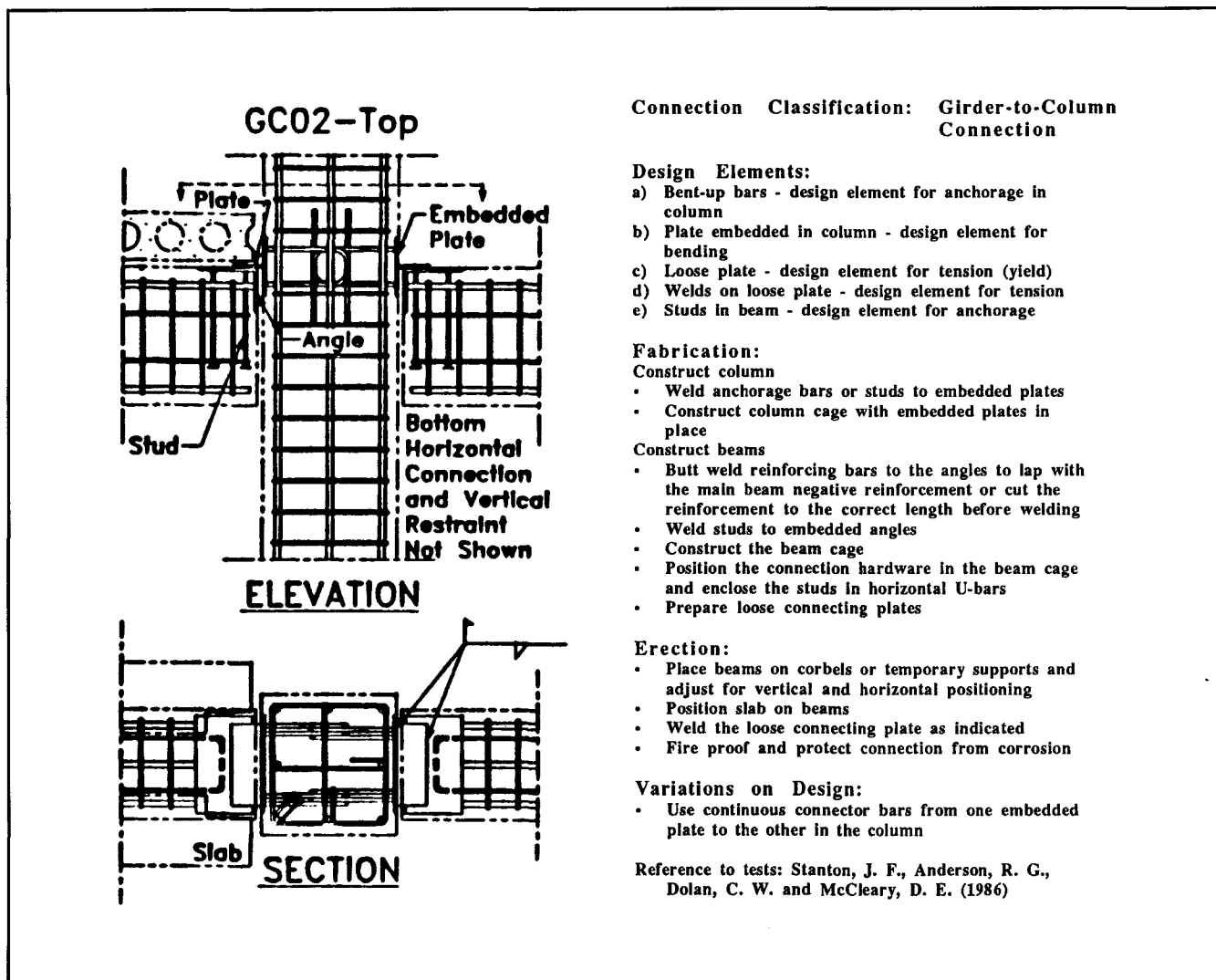Reference to tests: Stanton, J. F., Anderson, R. G., Dolan, C. W. and McCleary, D. E. (1986)

Fig. 1. Evaluation form.

the potential for energy dissipation by using friction connections made from automobile brake pad materials that slip at a predetermined load.

Several conceptual studies have been conducted, among the most useful of which is that by Clough.[12] It provides a thorough background into the problem of adapting precast concrete for use in seismic zones and gives a procedure for defining the strength and ductility demands on members and connections.

RESEARCH TASKS

Reliable connection behavior can only be verified by testing. However, there are too many connection ideas available to test them all, so some selection scheme is needed. The primary purpose of this project is to develop ways of classifying and evalu-ating connection details so that those with the most promise can be identified for further development, detailed analysis and ultimately, testing. The research was divided into the following tasks:

1. Collection of information. This was done by combing the public literature, sending out surveys to producers and designers, following up on personal contacts and other initiatives.

2. Initial classification and evaluation of connections. These are explained in the next section and were conducted by the researchers.

3. Presentation of connection research at industry workshops.

4. Updating and publication of connection classification and evaluation in the light of industry feedback. Selection of connections for further, more detailed, study.

5. Use of strut-and-tie (truss) models to identify the critical elements in the selected connections, and to provide a preliminary method of analysis.

6. Identification of critical components common to many connections. The intention is to permit testing to start at the earliest possible opportunity on elements, such as short but very well confined splices, that might be expected to be useful in many connections.

7. Development of recommendations for connections to be tested and the test parameters to be used.

Testing is to be conducted in Phase 2 of the PRESSS Research Program. The decision was made to concentrate most heavily on "dry" connections, since "wet" connections made with site-cast concrete may be used under the existing code. A dry joint system is usually viewed as more economical in North America.

Connection: GC02-Top
Source: Design and Typical Connections for Precast and Prestressed Concrete, PCI

Fabrication: (Rating - reasonable/good)
- Requires welding studs to embedded angles
- Requires shop welding of beam negative moment reinforcement to embedded angle
- Casting multistoried columns possible
- Embedded plates must be cast into the columns with adequate anchorage
Q.A.: fairly easy

Erection: (Rating - reasonable)
- Loose plates allow for on site adjustment
- The loose plates must be field welded to the embedded angles and plates
- Slab must be positioned
- The next floor can be erected before the work on one floor is finished
- Connection may require fire proofing and protection from corrosion
Q.A.: important: Welds are critical to structural performance

Structural Performance: (Rating - poor/reasonable)
Test Performance: (From PCI Research Report 1/4)
- A bulkhead was used in place of a column. Bottom connection was GC01-Bottom type.
- Connection was more flexible than a comparable monolithic reinforced concrete joint
- First crack formed across the top of the beam at the end of embedded angle. Crack propagated diagonally down the beam towards the bulkhead. The crack widened prior to sudden fracture of one of the rebars just past the point where it was welded to the embedded angle.
Field Experience:
- Unknown

Durability:
- Corrosion is possible without proper precaution

Ease of Repair: (Rating - reasonable/good)
- Easy if loose plates fail, more difficult if beam or column fails

Architectural Considerations:
- Produces a reasonably clean connection unless the corrosion protection/fire proofing is unsightly

Behavior Classification:
- Best suited for Rigid. Some Energy Dissipation possible. Not suitable for Extensible

Characteristics and Potential for Development:
- Detail the connection with the negative beam reinforcement on top of the embedded angle to reduce the eccentricity; may lead to congestion problems during welding
- Improve weld details

Overall Rating: Reasonable

Cost:	Fabrication	Erection	Finishing	Total
Mat'l Labor				
Total				

Fig. 1. (cont.). Evaluation form.

CONNECTION CLASSIFICATION AND EVALUATION

Connections were classified and evaluated in order to select those which have the most promise for being both structurally adequate in a seismic environment and readily constructible. A large number of connections, selected from many sources, were evaluated. The PCI Connections Manual[5] was used as the starting point. The connections were classified according to function: broadly as frame or panel connections, and in more detail as beam-to-column or column-to-foundation. The connections were then evaluated in two ways. First, they were judged in the areas of fabrication, transportation and erection, structural integrity, durability, ease of repair and architectural characteristics. It was not possible to apply exactly the same criteria to all connections because their configurations differed so much. But, as an example, the fabrication category included such issues as:

• The weight of hardware, which influences cost and ease of handling.
• How complex the hardware is to fabricate and assemble.
• The extent and complexity of welding.
• Restrictions imposed on the fabrication sequence of the members.
• Tolerance requirements.
• Ease and reliability of concrete placement.

The judgments in each category were made by using linguistic descriptors ("unacceptable," "poor," "acceptable," "good," etc.) rather than numerically, in order to avoid the temptation of averaging scores if numbers were used. An overall rating was then assigned. If the connection was rated unacceptable in any one category, then it was rated unacceptable overall. Otherwise, a subjective score reflecting the individual ratings was assigned. Cost has not yet been evaluated because it lay outside the expertise of the research team. Representatives from industry have offered to assign approximate cost ratings in the near future. They will be indicative rather than exact, because the sizes of the hardware elements are not fully detailed.

An example of the standardized presentation and evaluation format is shown in Fig. 1. All the connections have been evaluated in this format and together they constitute a compendium of details.[4] One page contains a drawing of the connection, a description of one way of constructing it and a reference to the source documentation if any exists. Sizes are not shown, since they obviously depend on the forces applicable in the particular situation. The construction method was taken from the source documentation when it was given, but usually had to be assumed. It was included because it forms the basis for the ratings of fabrication and erection.

Many beam-to-column connections can be broken down into a top horizontal, a bottom horizontal and a shear (or vertical) component. By mixing and matching, many connections can be made up from these components, so they were recorded and evaluated separately to minimize duplication. The second page shows the individual ratings and summarizes the reasons for them.

The second part of the evaluation was to consider the type of structural response, or performance type, which could be achieved. The three types are rigid, energy-dissipating and extensible. In many cases a connection can be made to exhibit more than one performance type by selecting different component sizes.

Rigid Connections

A rigid connection is one designed in such a way that it never yields, by making sure that the ratio of strength to applied force is higher at the connection than in the adjacent members. For example, a column-to-column frame connection can be made rigid by placing it at mid-story height, since the bending moment there is close to zero, whereas it is a maximum at the beam-to-column junction. A beam-to-column connection may also be made rigid, but only with difficulty, since the inelastic action must be forced into adjacent regions where the applied moment happens to be smaller. This usually requires the connection to be very strong.

Energy-Dissipating Connections

The energy-dissipating and extensible connections are subdivisions of what are sometimes thought of as ductile connections. In the energy-dissipating category, the components must have sufficient inelastic deformation capacity to undergo the imposed strain history, but they must also dissipate enough energy by hysteresis to damp out the vibrations of the structure. This may be done in a number of ways, such as yielding of steel or slip at a friction interface. Fig. 2 shows an example, in which the bars yield alternately in tension and compression.

Extensible Connections

In an extensible connection, the components must be able to undergo the imposed deformations in one or more senses, while remaining strong in another. A simple beam seated on an elastomeric pad on a corbel is an example. The connection permits horizontal movement and end rotation, but remains strong vertically. A second example is shown in Fig. 3, in which the connection is configured so as to allow the panels to move apart or together when subjected to thermal movements, but to remain strong against shear forces.

Discussion

The purpose of considering these performance types is to force the designer to plan precisely how he or she intends the structure to work. Cast-in-place concrete construction contains no discontinuities, and reasonable ductility throughout the structure is assured by detailing the structure according to the UBC. Thus, the integrity of the structure is not threatened if inelastic action occurs in a different location or sequence to that originally envisioned. By contrast, in a precast concrete structure with dry joints, the connections usually represent serious discontinuities at which inelastic action will concentrate.
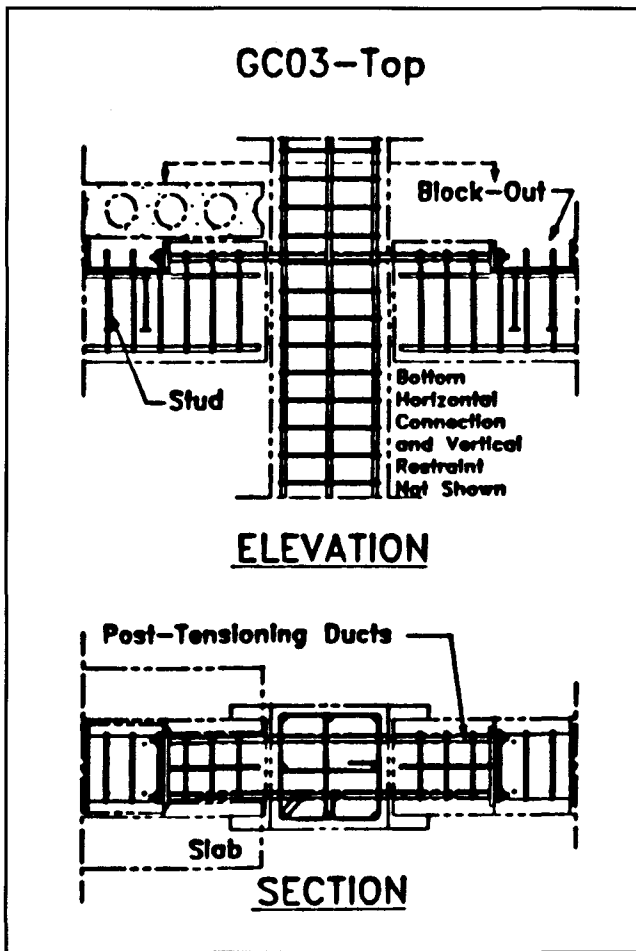
The extent of the inelastic deforma-
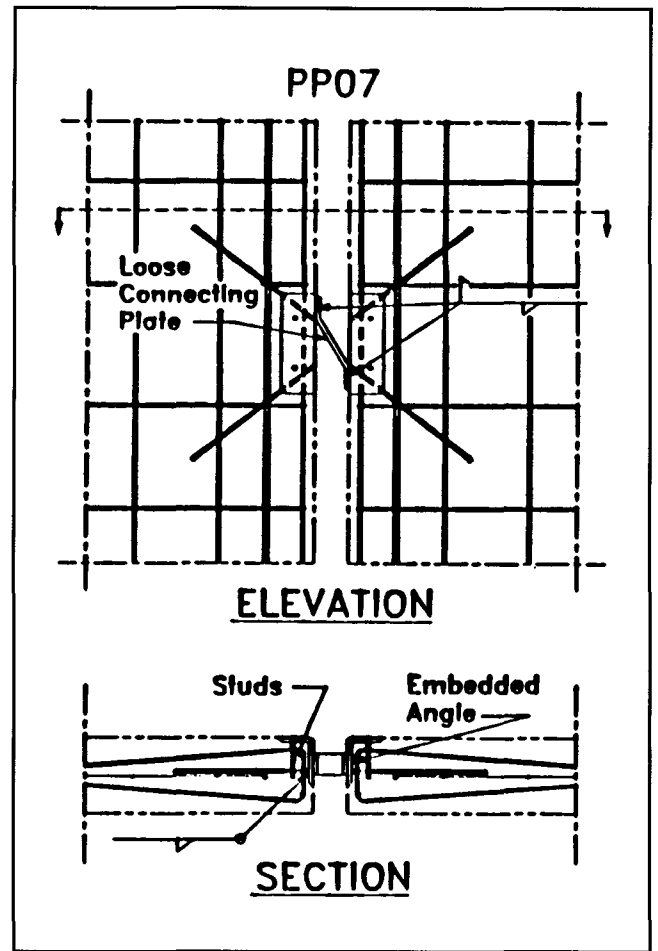
Fig. 2. Energy-dissipating connection.

Fig. 3. Extensible connection.

tion must, therefore, be predicted realistically[12] and the connections must be detailed accordingly. This requirement raises the issue of overstrength components. The element in a connection designed to yield must be the weakest, and if an overstrength material is supplied, some other link in the chain may become the weakest part and may not be ductile, thereby leading to brittle failure. Thus, an overstrength material could be just as undesirable as an understrength component.

This classification and evaluation procedure is somewhat different from that being used in the Japanese research. There, the objective is always to make the structure behave like a cast-in-place system, so the connections are typically made with cast-in-place concrete or grout. Furthermore, much of the research and development is conducted by construction companies, and most of the big firms have now developed their own proprietary systems. For the researchers to pass judgment on these systems is

considered inappropriate, so no ratings are being assigned in Japan.

The majority of connections found in the literature were evaluated in this way, and individual ones were omitted at this stage only if they appeared much too difficult to construct or contained serious obstacles to development for seismic use.

Industry Feedback

The process was subject to feedback from industry on two occasions. Before starting, the researchers visited several local producers, contractors and designers to seek their advice on the issues to be included and the criteria to be used in rating the connections. Then, in April 1991, industry workshops were conducted in Seattle, Chicago, Atlanta and Los Angeles. These workshops were sponsored and administered by PCI and addressed both systems and connections, and are described in detail in References 2 and 13. They provided a forum for small

group discussions of the system concepts and connection details being studied by the researchers, and part of the feedback concerned the connection evaluation procedure.

This interaction confirmed that the appropriate broad categories of information were indeed being included, although there was some discussion on certain details, such as whether to subdivide the ease of erection into two parts, the first to address the temporary erection connection and the second, the permanent connection. The workshop participants were asked to rate two connections in the individual categories and overall, with the intention of using their ratings for calibrating the researchers' evaluation. The average of the industry participants' ratings is shown in Fig. 4. Somewhat surprisingly, the individual ratings showed very wide scatter, thereby rendering dubious the value of refined calibration. However, the average corresponded to the researchers' ratings, and this was taken as an affirmation of

Evaluator's name:		Mr. Average			
Connection name:		GC-05 bottom			
Behavior Classification(s):		Rigid			

Criterion	Rating	Comments	$ Mat'l	$ Labor	$Total
	(A-F)	(free-format!)	(H/M/L)	(H/M/L)	(H/M/L)
Fabrication	C	Plates require form cutouts	M	M	M
Erection	B	Little tolerance. Lots of crane time.	M	H	H
		No temporary support needed.			
Struct. Performance	C	Limited torsional capacity, especially during erection. Ductile if plates are weakest element.			
Durability	B	OK if plates covered by mortar.			
Ease of Repair	D	Nearly impossible if plates fail in shear.			
Architectural	B	Must be covered by mortar. Patch could be ugly.			
Total	B -		M	M/H	M/H

Fig. 4. Summary of industry connection evaluations.

the researchers' process.

Several points emerged from the discussions. Only those germane to connections are given here. First, the method of construction, the overall system and the connections must all be planned together. For example, low rise buildings are often most conveniently constructed using mobile cranes and "up-and-out" construction, whereby construction starts at one end of the building and proceeds full-height along to the other. In this case, connections which require floor-by-floor activities, such as full-length post-tensioning, impose serious penalties on the construction sequence.

Second, regional differences mean that no solution is universally applicable: in the Midwest thermal effects are critical but on the West Coast, even though thermal movements must still be taken into account, seismic loads dominate. This has profound effects on the design of the connections. Even within a given region, differences of opinion were frequent and were usually attributable to the expertise and equipment developed over the years by individual contractors and producers.

Certain features of connection hardware are likely to lead to poor structural performance and therefore should be avoided if possible. Site welding of reinforcement raises problems of quality control and the possibility of embrittlement in the heat-affected zone. Eccentricity in the load path within the connection is likely to lead to local kinking of the components, which causes high inelastic strain demands. These are particularly damaging if they occur near welds, since they can lead to premature bar fracture. The number of load transfers in a connection (e.g., from one bar to another) may be used as a rough measure of the connection's complexity, which in turn is an indicator of its reliability, ease of fabrication and cost. Thus, excessive numbers of load transfers are undesirable.

In many connections, the interests of the engineer, the producer and the contractor differ, and the needs of all three must be recognized in order to achieve a good solution. The main cause of the difficulty is geometric: the dimensions of the connections are much smaller than those of the member itself. Thus, while ± 0.5 in. (13 mm) may represent a tolerance of only 0.1 percent on the overall length of a beam, that error must be accommodated by the connection, within which it might represent 10 percent of the connection dimension, thereby causing a significant eccentricity. A useful design approach is, therefore, to try to arrange that directions in which member dimensions can be least tightly controlled do not coincide with directions in which the connection is sensitive to eccentricity.

Energy dissipation was discussed at the workshops, particularly how much is needed and how to achieve it. The first question is not addressed explicitly for other forms of construction, such as steel or cast-in-place concrete, and furthermore the necessary rate of energy dissipation cannot be calculated exactly in ft-lbs per second.
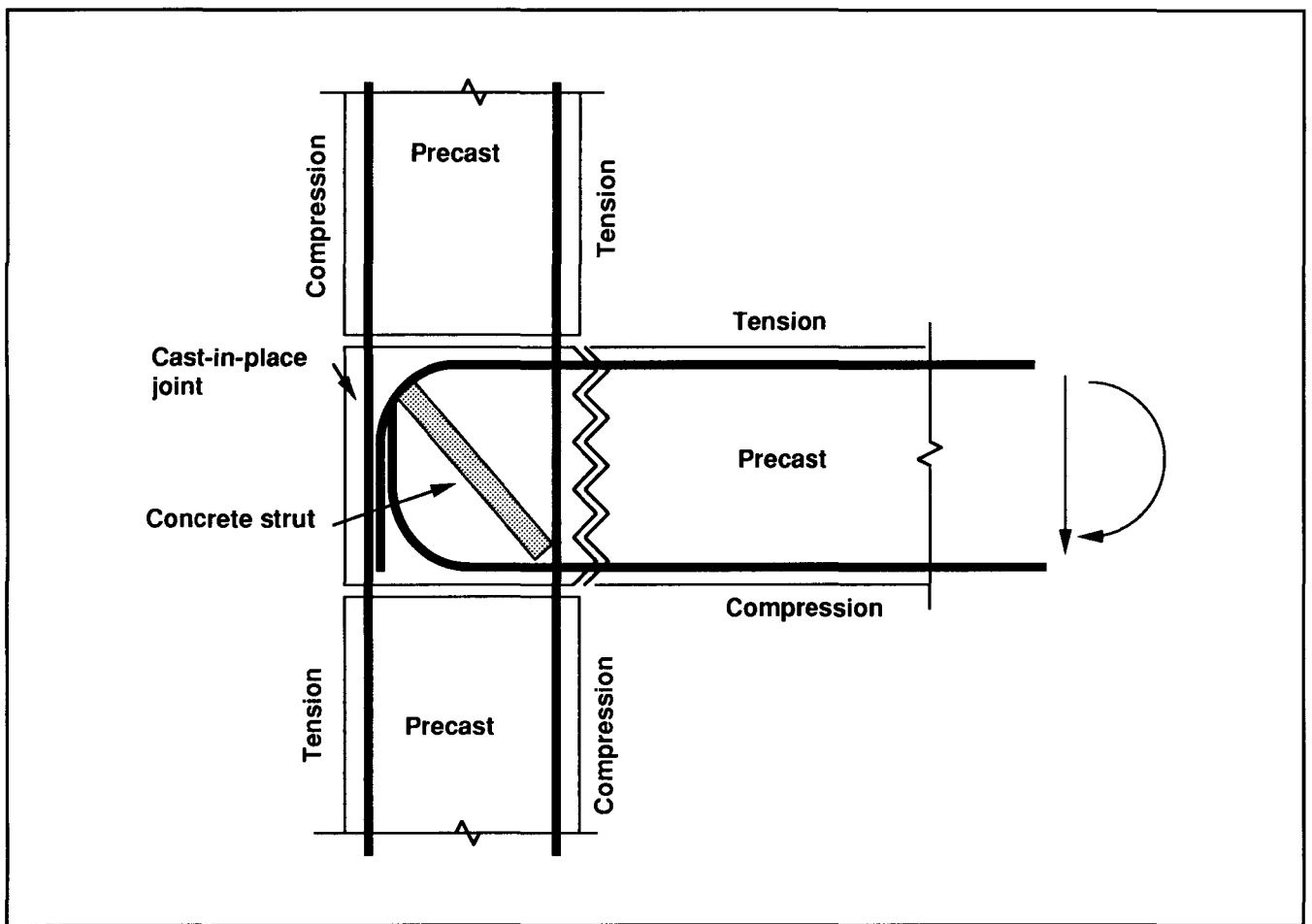
Fig. 5. Strut-and-tie model.

Rather, it is known from experience and testing that buildings satisfying the detailing provisions of the UBC generally dissipate enough energy to perform well in earthquakes. This apparent vagueness is partly a consequence of the difficulties in defining precisely future earthquake motions.

If energy is dissipated by yielding of metal, the volume of material activated is important, since materials can only absorb and dissipate a certain amount of energy per unit volume (i.e., the modulus of toughness, which is defined as the area under the complete stress-strain curve to fracture). Thus, yielding a large volume of material is desirable if energy is to be dissipated without inducing dangerously large strains. In cast-in-place construction this debonding occurs naturally over a distance equal to about twice the plastic hinge length, which itself is about equal to the effective depth of the beam.

On the other hand, in precast concrete the steel may have to be debonded from the concrete artificially in order to yield the desired volume of steel before the connection suffers local failure. Compton and Mast[14] have used a novel approach to solving this problem by reinforcing a deep spandrel beam with an unbonded cross-brace made from a steel flat bar. The steel thus yields over its full length, and the concrete panel surrounding it ensures that it yields rather than buckles in compression.

Modeling

Analysis for design requires analytical models. Because so many connections can be developed, such models should be simple but should still reveal the essential features of behavior. Truss, or strut-and-tie models[15] appear to be well suited to the job and they are being developed for the most promising connections. They are useful because they allow the designer to identify easily the functions performed by each element of the connection and

to obtain approximate magnitudes for forces. An example is shown in Fig. 5. It shows, for example, that the critical function for the hook on the top bar is to transfer tension to the back column bar by lap splicing. If it cannot do so, the diagonal compression strut cannot form across the concrete core. (This observation is not restricted to precast concrete.)

The connection region can generally be thought of as containing three distinct parts – the connection hardware, the zone of anchorage to the member, and the body of the member itself. These three form a chain and the designer must choose the link in which the inelastic action is to occur. Forcing yielding into the connection hardware has the attractions that the members may be protected from damage and that in many cases repair becomes feasible by repairing or replacing part of the connection. However, the elements of the connection must be carefully detailed in order to ensure suitably ductile behavior,

whether they are intended to be energy-dissipating or extensible.

The anchorage zone is usually a poor choice for inelastic deformation because ductile behavior is unlikely and satisfactory repair is difficult. However, it is rather vulnerable and is easily overlooked. For instance, if reinforcing bars are used to anchor a piece of embedded steel, the concrete will start to crack when tension stress in the the bar reaches only about 5 ksi (35 MPa).

Serious cracking of the anchorage zone must thus be expected before the full yield strength of the bar can be reached. Thermal effects are a common cause of anchorage zone problems because the members are often much stiffer than the connections, thereby forcing the change in dimensions of the members to be taken up by local deformations in the connection region. The high stresses so induced can cause damage to the anchorage zone if it is not detailed appropriately. Any such damage reduces the likelihood of good response in a subsequent earthquake.

If yielding is forced away from the connection region and into the body of the member, conventional cast-in-place detailing can be used to ensure ductile behavior there and the volume of material available for energy dissipation is usually adequate. Repair may be difficult if damage is serious, but this is also true of other forms of construction and may not be an important criterion in the event of a severe earthquake. (The primary design criterion in a severe earthquake is to avoid collapse and loss of life: damage to the structure is accepted as unavoidable.)

A second level of modeling is needed to establish the relationship between design loads and available ductility in precast concrete construction. This lies outside the scope of the present project. In it, inelastic dynamic analysis will be used to predict the response of typical precast concrete structures to seismic loads, and thereby relate the inelastic displacements to the lateral strength of the structures. It will be conducted in a subsequent phase of the PRESSS project, using the computer programs developed in PRESSS Project 1.4.

ONGOING AND FUTURE ACTIVITIES

The building systems presented at the workshops are now being modified in the light of feedback obtained there. The connections that were suggested for use with them were presented in a conceptual form and they are now being developed and detailed to be used with the modified building systems.

For now, element forces and sizes are being based on seismic loads calculated for cast-in-place concrete construction. They can be updated later when more refined estimates of the loads appropriate for precast structures are available.

In addition to these activities, a list will be prepared of "basic component research" topics to allow early testing to start on components that are deemed useful for many connections. Hardware will be designed for several widely applicable complete connections in addition to those for the example buildings.

Lastly, some simple Single-Degree-of-Freedom (SDOF) nonlinear dynamic analyses will be conducted to investigate the relationships between design strength and ductility capacity in systems which have hysteretic properties typical of precast/prestressed concrete. These latter studies will not provide definitive answers, but will be useful precursors of the more detailed studies to be conducted in the next phase of PRESSS.

SUMMARY AND CONCLUSIONS

The Connection Classification and Evaluation Project of the PRESSS Research Program has now been under way for approximately a year. A classification and evaluation scheme has been established and has been verified by feedback from industry at four workshops. A large number of connections, including many from the PCI Connections Manual,[5] have been evaluated and assembled in a standard format in a compendium.

Appropriate dimensions and details for the most promising of these connections, together with other connections selected as suitable for the buildings being developed in PRESSS Project 1.1, are now being developed using analyses based on truss models. The results from these studies will be used to develop recommendations for connections to be tested and parameters to be examined.

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