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Seismic connections for precast concrete structures

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ABSTRACT: A method of classifying and evaluating connections for precast concrete structures in seismic zones has been devised. It is used to select the most promising connections for physical testing and provides insights into the design of the connections.

1 INTRODUCTION

1.1 Precast concrete

Precast concrete has several features which are desirable in a building material, including tight quality control in a production plant, multiple of use forms and speed of erection. However, in the last decade some of these inherent advantages have been eroded by improvements in cast-in-place concrete technology, such as flying forms and admixtures that shorten curing times. The result is that, in non-seismic zones of the USA, competition between these two building systems is fierce.

1.2 Seismic issues

In seismic regions the situation is complicated by the need to design for dynamic loading. Most philosophies of seismic design demand that the structure possess toughness and ductility, because economics prohibit designing a structure to remain elastic even for moderate earthquake motions. Furthermore, ductility is essential for providing some protection against the effects of an unexpectedly large earthquake.

Design forces are less than forces predicted on the basis of elastic behavior by a factor, R_W, that depends primarily on the ductility capacity of the system. Ductility capacity is difficult to compute reliably from fundamental material properties, so building codes such as the Uniform Building Code (Uniform 1988) contain prescriptive requirements for reinforcing details that are intended to ensure the existence of the ductility needed to justify the codified force reduction factors. These details have been developed by testing and field experience and this prescriptive approach has, on the whole, worked.

The detailing requirements for reinforced concrete were developed for cast-in-place practice, and pose difficulties for precast systems primarily at joints. If the system consists of precast elements joined by suitably located cast-in-place joints, satisfaction of the prescriptive detailing requirements may be possible. From a regulatory point of view the structure may then be considered to be a cast-in-place one, and the behavior may also be expected to be similar. This approach is referred to as "emulation" and enjoys widespread use in New Zealand and Japan.

Emulation is less commonly used in the United States. First, the precast industry grew up mainly on the east coast of the country, distant from the most obvious seismic threats, and so connection details were developed which were most strongly influenced by criteria such as ease of assembly and price. These conditions are most easily fulfilled by "dry" connections consisting of welds, bolts, etc., and such connections continue to be favored by the industry. Second, most precasting is done by specialist subcontractors and for reasons of contractual responsibility there is a natural reluctance to mix the dry (precast) and wet (cast-in-place) trades on site.

Dry connections in a precast structure usually constitute discontinuities of strength and stiffness which can be expected to attract deformations and damage during an earthquake. This concentration increases the local ductility demand, and, unless the connection details are carefully designed, their ductility capacity is likely to be inadequate. The research needed to develop dry connections suitable for seismic resistance has not been done, so the UBC contains no prescriptive detailing requirements for precast concrete. Precast structures must therefore satisfy the UBC requirement that they possess "equivalent lateral force resistance and energy absorption capacity" so that the design rules for reinforced concrete, developed for cast-in-place construction, may be used. No paradigm for proving equivalence exists, and building officials have little incentive to develop their own, so the resulting regulatory obstacles have inhibited the use of precast construction on the west coast of the United States.

1.3 Role of PRESSS

In 1990, the National Science Foundation and the Precast Concrete Institute (PCI) funded the US-Japan joint Precast Seismic Structural Systems (PRESSS) research program to develop precast concrete systems suitable for use in seismic zones. Five individual projects were funded in Phase I, as described by Priestley (1991) The work described here falls within the project on 'Connection Classification and Evaluation' (Stanton, 1991). It has been conducted in close cooperation with the other individual projects within the program, especially the studies on systems described in Nakaki (1991), and with the Japanese researchers conducting parallel studies (Watanabe 1991).

Development of suitable connections is essential to the overall goals of PRESSS, and that development must include testing. However, many more connection concepts have in the past been proposed or tried than can realistically be tested, so some means of screening is needed. The primary objective of the research project is thus to produce a method of classifying and evaluating connections that will allow the best existing ones, or derivatives of them, to be identified for testing in Phase II of the program, which is starting in 1992. In addition to the evaluation, some development work is being conducted and analytical models are being generated.

The purpose of the modelling is twofold. First there is a need to understand the global behavior of the structural system, since that defines the local forces that the connections must resist. The design loads for the structure, from which the connection forces can be calculated, must ultimately be defined in a way that can be codified, such as the R_w format presently used in the UBC for other construction systems. The relationship between global response and connection forces also emphasizes the inextricable linkage between the connection characteristics and and those of the system, and the consequent need for coordination between individual research projects within the overall program.

Second, methods are needed for detailed design of the connections, once the forces acting on them and the ductility demanded of them are known.

2. PREVIOUS WORK

Many seismic connections have been tested and used in New Zealand (e.g. Park, 1981) and Japan (e.g. Izumi, 1986), but almost all of them have used the emulation approach and so are not central to the present study. In North America, a wide-ranging study for PCI (Stanton 1986) included tests on seventeen commonly used connections, but loading was monotonic in most cases. A number of investigators have conducted cyclic load tests on a limited class of connections for frame buildings (French, 1989) or panel buildings (Rizkalla, 1989). The National Institute for Standards and Technology is at present studying precast seismic systems assembled using prestressed steel (Cheok, 1991).

3. PRESENT RESEARCH

3.1 Connection Classification and Evaluation

Connection details were collected from many sources. Most of the connections were not specifically intended for seismic service, but were included in this study because they have been used or tested and because it may be possible to develop from them a detail suitable for seismic resistance. The PCI Connection Manual (Design 1989) provided many connections, since it reflects the range in use today. Others were obtained through a literature search and through contacts with individual precasters and engineers.

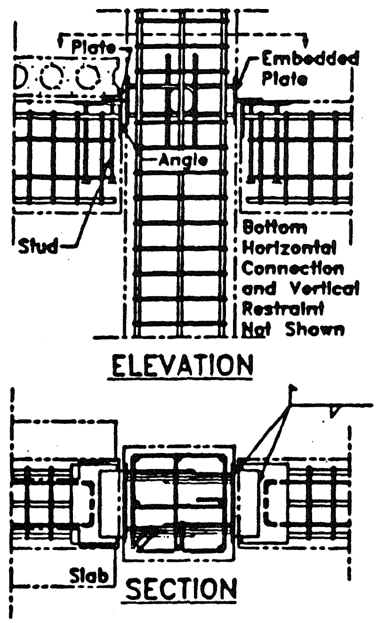
A system for classifying and evaluating connections was then developed and was refined by applying it to the previously collected details. The classification system distinguished between panel connections and frame connections. This distinction is not absolutely unique, since some connections may be useful in both contexts but it is useful because most precast structures fall into one of the two categories.

The connections have been recorded in a standard format, shown in Fig. 1. Schematic drawings show the essential components and narrative describes the elements that must be designed and the assumed fabrication and erection sequence.

The evaluation covered eight attributes of the connection: Fabrication, Erection, Sructural Performance, Durability, Ease of Repair, Architectural Considerations, Behavior Classification and Potential for Development. In each category the connection was judged to be "unacceptable", "poor", "reasonable" or "good", then the ratings in the individual categories were combined to give an overall rating for the connection. An example is shown in Fig. 2. If the detail was deemed unacceptable in any one category (e.g. Erection, because excessive site welding was needed) then it was rated unacceptable overall. Otherwise the overall rating reflected the average of the individual ones. The purpose was to separate those with potential from those without rather than to generate a quantitative ranking, so the need for subjective judgements was not a drawback. Many connections appeared to have potential in some circumstances (e.g. low seismic zones) but to pose difficulties in others (e.g. severe seismic zones).

The judgements took into account as many of the important attributes of the connection as possible. For example, the evaluation of Ease of Fabrication took into account such matters as the weight of the hardware, the extent and complexity of welding, requirements for form penetration, the ease with which the hardware could be placed in the forms, restrictions on member fabrication sequence, tolerance requirements, ease and reliability of concrete placement. The judgements were made by the researchers, but local fabricators and contractors helped at the start of the process, in order to ensure that the important issues were properly addressed.

GC02–Top



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 Typical connection record.

3.2 Behavior Classification

The behavior classification merits more detailed explanation. The original categories chosen for it were 'Rigid', 'Energy-dissipating' and 'Extensible', but after considerable discussion at the October 1991 US-Japan joint meeting the names of the first and last were changed to 'Strong' and 'Deformable' because those words represented better the underlying concepts. The categories were devised as a way of forcing the designer to plan exactly how the structure would perform in an earthquake rather than simply designing the connection for a specific strength based only on a code-specified equivalent static loading. This is more important in precast than in cast-in-place construction because of the probable concentrations of ductility demand at the connections.

The Strong Connection is intended to force all inelastic deformation to occur in the adjoining precast elements rather than in the connection. This can be arranged by ensuring that the ratio of induced force/available strength is smaller at the connection than elsewhere. Either the connection can be made very strong or it can be located at some point at which the internal forces are small. A column splice at mid-storey height in a seismic frame is an example of a connection which is Strong by virtue of locating it at a point of negligible bending moment.

The Deformable connection is intended to have sufficient inelastic deformation capacity to undergo many cycles of displacement without fracturing and without loss of function in other directions. However, it does not need to do work during the deformations, so there is no strength requirement. An example might be a simple beam-column connection formed by a bearing pad, such as might be found in the interior of a structure whose seismic resistance comes from the perimeter frame. The connection would then be classified as being Strong in shear and Deformable in bending, because the rotations should occur without jeopardizing the resistance in other directions (e.g. shear) and without the need to induce a resisting moment. A second example might be a panel connection that must allow temperature and shrinkage strains to occur freely in order to avoid cracking, yet must be stiff and strong in shear to resist deformations due to earthquake forces. Such a connection would be described as Strong in shear but Deformable in tension.

The Energy-dissipating category is similar to the Deformable one, except that the connection must also have sufficient resistance to provide the energy dissipation needed to damp the motion of the structure.

Many connections could be adapted to fit at least two out of the three behavior classifications, depending on the size of the components (bars, studs, plates, welds, etc.). However, the behavior classification must be chosen as part of an overall decision which includes many other features of the structural system. For example, Strong connections may be attractive because the inelastic action can be restricted to the body of the member, where ductile detailing is easier to achieve. However, if the connections are rendered Strong by using a cruciform shape, such as used in Lum (1981), transportation may be more expensive because fewer units can be

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				

transported on one vehicle. If the members are three-dimensional (e.g. columns with four projecting beam stubs) transportation costs may become prohibitive, so site-casting may prove economical. It is thus clear that the characteristics of the connections must be chosen as an integral part of the planning of the structure, and cannot be left as an afterthought.

3.3 Industry Participation

PRESSS Industry workshops, reported by Nakaki (1991), were conducted in Seattle, Chicago, Atlanta and Los Angeles in April 1991 both to disseminate to representatives of industry ideas on systems and connections and to obtain feedback from them. The participants included designers, fabricators and contractors. The workshops demonstrated a remarkable diversity of opinion among disciplines (e.g. designers versus contractors), in different regions (as expected, because of the diverse seismicities) and even within one region. The latter appeared to be influenced by contractors' investments in particular plant, equipment and personnel training.

The participants also evaluated some connections according to the proposed method; their judgements confirmed that the technique was reasonable.

Three important points concerning configuration of hardware also emerged from the workshops. First, the number of load transfers from one piece of steel to another was suggested as a measure of the complexity of the connection. More transfers generally mean higher cost and lower reliability. Second, eccentricity in the load path was deemed to be undesirable, because severe kinking of reinforcing bars and possible premature brittle failure can occur even in monotonic load tests, as reported by Stanton (1986). Under dynamic loading, the consequences could be expected to be even more serious. Last is the issue of tolerances, in which questions of scale cause problems. Because the dimensions of the member are at least an order of magnitude larger than those of the connection, small relative errors in member dimensions can mean that adjustments must be made during erection which are relatively large compared to the size of the connection. This can lead to serious eccentricities in the load path. It is important, but quite difficult, to design connections which allow for reasonable inaccuracies during fabrication without jeopardizing structural performance.

3.4 Modelling

Simple mathematical models are being developed for the most promising connections. The designer of the connection needs to ensure that a clear load path exists for the forces that must pass through the connection, and this process requires the selection and placement of suitable reinforcement. The need is therefore for a *design* model rather than an *analytical* one, so strut-and-tie (or truss) models of the type described by Marti (1985) are being used. Load paths can be chosen using statics alone without resorting to more complicated analysis. The transfer of loads between different components of the connection still remains to be verified and this is best done by testing, such as that planned for Phase II of the PRESSS Program.

These modelling efforts have already shown that most connections can be subdivided conceptually into three regions: the connection hardware, the zone of anchorage to the member and the body of the member. These regions correspond approximately to the 'interface', the 'D-region' and the 'B-region' used by others (e.g. MacGregor, 1992). The designer must choose the location of the inevitable inelastic action and must then detail the different regions in accordance with that choice.

For example, if the Strong Connection concept is chosen, then both the connection hardware and its anchorage to the concrete must be made stronger than the body of the member. The latter is likely to be the more difficult of the two. If the yielding is to take place within the connection hardware itself, for example, with the intention of confining damage to that region and then replacing the hardware after an earthquake, then the other two components must be made strong enough to prevent yield. Again, the anchorage is likely to pose the most difficult problems, since the yield strain of steel is much larger than the cracking strain of the concrete in which it is embedded.

A further problem is caused by materials which may have strengths which exceed their guaranteed minimums. Even if the connection steel is 50% stronger than specified, the anchorage region must still not fail because doing so might render the connection brittle. In this case partial safety factors on strength that are greater than 1.0 are needed to ensure the correct behavior of the system. This concept may be new to designers accustomed to thinking only in terms of static strength, in which case more is better. Under dynamic loading, where avoiding brittle failure is crucial, this is not necessarily the case.

4 SUMMARY AND CONCLUSIONS

A wide variety of connections for precast concrete frame and panel structures have been collected, classified and evaluated in accordance with a method intended to identify those with the greatest potential for further development. The best of these will be refined and will then be tested in Phase II of the PRESSS program, which is now starting.

Simple mathematical models of sample connections have revealed several important design principles. Further modelling of the most promising connections is taking place to ensure that suitable components can be chosen in a rational manner.

Feedback from industry has confirmed that the evaluation process is appropriate and has provided valuable insight into the constraints on design arising from different disciplines within the industry.

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