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VILAS MUJUMDAR
VSM Assoc. Vienna, VA, USA

A HOLISTIC APPROACH TO PREVENT AND ANALYZE FAILURES IN PRECAST CONCRETE BUILDINGS STRUCTURES

HOLISTYCZNE PODEJŚCIE DO ZAPOBIEGANIA I ANALIZY AWARII W SPRĘŻONYCH KONSTRUKCJACH BETONOWYCH

Abstract Building codes are necessarily written to address the component design. The analysis of the structure which is left to the designer may involve a simple to very sophisticated techniques. An obvious weakness in this approach results at the interface of components and structural systems, which is frequently an area where failures initiate. Not sufficient attention is given to connect components and systems to provide structural integrity that is intended. This could be particularly dangerous in precast concrete building structures where the overall structural behavior is primarily dependent on the connection behavior and integrity. Of specific interest is also the interactive behavior of different materials with precast concrete, used in connecting components, such as reinforcing steel, structural steel, prestressing steel and cast-in-place concrete. Another factor that complicates the detailing of prestressed concrete components is that rigid connection for structural integrity has adverse effect on long-term behavior as no relief is provided for creep and shrinkage effects. Structural failures need to be studied from two different aspects: actual loads versus intended loads prescribed in codes; behavior of components/systems versus intended design basis. In precast concrete structures, the sequence of construction is also important which is generally not important in other type of structural building systems. Under lateral loads, excessive drift may cause reduced gravity load carrying capacity in non-lateral load resisting systems causing unintended failures. Finally, in some circumstances such as earthquake hazard, where the actual inertial loads depend on the mass of the component, redistribution of loads occurs subjecting some components to excessive loads beyond their capacity. The author has been involved in design, manufacture, analysis, and building codes/regulations development for precast concrete building structures as well as in analyzing precast concrete structural failures for the past 40 years. Some specific examples of each type of failure and possible causes are presented.

Streszczenie Normy budowlane dotyczą projektowania elementów. Analiza konstrukcji obejmuje proste lub bardziej skomplikowane techniki. Oczywista słabość w takim podejściu jest w przejściu od elementu do układów konstrukcji. Jest to miejsce w którym często powstaje zagrożenie awarii. Nie wystarczającą uwagę zwraca się na połączenia elementów i układów, w celu zapewnienia integralności strukturalnej, która jest zamierzona. Może to być szczególnie niebezpieczne w prefabrykowanych konstrukcjach budowlanych, gdzie ogólne zachowanie konstrukcji zależy przede wszystkim od dobrej pracy złączy. Szczególne znaczenie odgrywa także zachowanie się różnych materiałów takich jak stal zbrojeniowa, stal konstrukcyjna, stal sprężana czy betonu, używanych do połączeń. Utrudnieniem w projektowaniu konstrukcji sprężonych jest fakt, że sztywne połączenie ma negatywny wpływ na długotrwałe zachowanie się konstrukcji, nie pomaga w tym także skurcz i pełzania. Uszkodzenia konstrukcji muszą być analizowane uwzględniając dwa różne aspekty: rzeczywiste obciążenia w porównaniu z obciążeniami przedstawionymi w normach; zachowanie się elementów/układów w porównaniu z podstawowymi zamierzeniami projektu. W prefabrykowanych konstrukcjach betonowych, kolejność wbudowania, w przeciwieństwie do innych budowli, stanowi również istotny czynnik.

Pod obciążeniem poprzecznym, nadmierne przemieszczenia mogą spowodować zmniejszenie nośności układów podłużnych prowadząc do niezamierzonych awarii. Wreszcie, w niektórych okolicznościach, takich jak zagrożenie trzęsieniem ziemi, gdzie rzeczywiste siły bezwładnościowe, zależą od masy elementu, redystrybucja sił powoduje poddanie niektórych elementów nadmiernemu obciążeniu, powyżej ich nośności. Autor brał udział w projektowaniu, produkcji, analizie i rozwoju norm/rozporządzeń budowlanych dotyczących prefabrykowanych elementów betonowych konstrukcji budowlanych, jak również i w badaniu awarii ww. elementów w ciągu ostatnich 40 lat. Przedstawione zostały niektóre szczególne przykłady każdego rodzaju awarii oraz ich możliwe przyczyny.

General

Structural failures occur around the world regularly. These range from small pedestrian bridges to large buildings. Although it is difficult to generalize the causes of failures as the codes and regulations differ from country to country and in some cases within a country, to differences in construction and design practices, there are some common themes in every failure.

This paper deliberately avoids discussing poor construction practices around the world, specifically in developing countries. The main purpose of this paper is to emphasize that failure analysis needs to be conducted on a holistic–basis considering the behavior of the entire structure. The reason for this emphasis is that building codes are written for component design based on the forces generated by system analysis. Another area of concern is assumed load versus actual loads on the structure. Finally the actual behavior of components/system can be significantly different than intended in the design.

Precast Concrete Buildings – Background

As compared to other building materials, precast concrete poses unique challenges as a structural material for buildings. Use of precast concrete as architectural façade for buildings is not considered here primarily because it is not considered in the overall building structural analysis, although has significant impact on building behavior in some cases. Precast concrete systems by their very nature are constructed by assembling components produced primarily in a manufacturing facility which are then transported to the project site and assembled into a building structure. This type of assembling a building structure has unique considerations:

1. Loads imposed on individual components when being lifted out of forms in a manufacturing facility may be different than in their final positions. Wall panels are often cast in vertical forms, or in horizontal forms that are tilted to vertical before the panel is lifted out
2. Panels should be stored, transported and handled in a near vertical position at all times. These panels may not have sufficient strength to resist gravity loads if laid flat
3. Loads imposed on individual components during transportation and erection may be different than in final position
4. Interaction of connection hardware with components/subsystems needs to be understood

Allowable lifting and handling stresses are determined by the degree to which cracking can be tolerated. Units need to be designed to be handled with no visible cracks, or to be handled in a manner that restricts the crack widths to acceptable limits for the environment that the unit will be exposed to in service. Lifting and handling concrete flexural stress calculations should be calculated with an impact allowance of 50% for transport and handling.

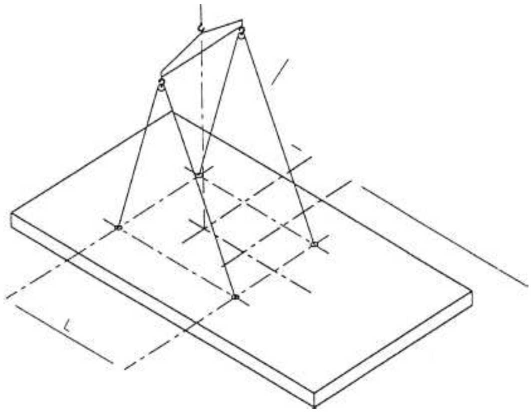

Fig. 1. Panels Lifted from forms – Flat (Courtesy NZ report)

For precast units that must be transported over rough terrain, an additional impact factor should be allowed.

Fig. 2. Proper Storage of precast panels

Fig. 3. Erection of precast Panels-vertically

There is a fundamental assumption in precast concrete building assemblage; that the structure assembled by joining different components behaves as if it were a monolithic concrete structure. The connections are designed to realize this assumption. Such an assumption in analysis/design may or may not be true as the overall structural behavior is highly dependent on the behavior and types of connections that join various components.

Connections

Connections can be classified in two broad categories. The design philosophy, for each type is briefly described below:

1) Strong connections, and
2) Ductile connections

1.Strong Connections

- The connection is stronger than the adjacent members, so the yielding takes place away from the connector,
- The connection theoretically needs no ductility and in practice is supplied with little ductility,

– Absolute strength is less important than the ratio of capacity/expected demand

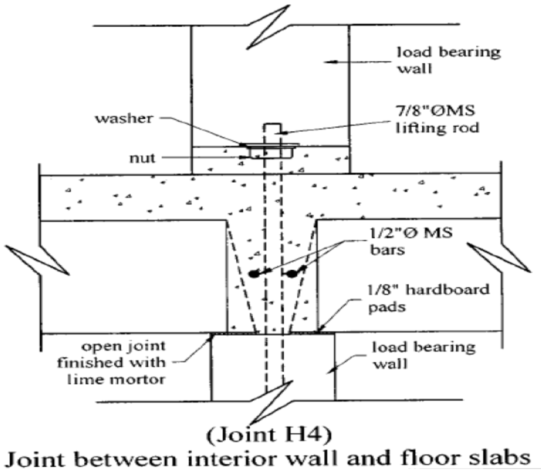

Fig. 4. Ronan Point Tower – East London (Strong Connection, panel failed)

2. Ductile connections

– Ductile connections possess significant strength and form part of the lateral load resisting system.
– They can yield cyclically and dissipate energy to provide useful structural damping.
– Connections can be welded when the embeds are made stronger than the connecting plate.
– They can also be made with splicing reinforcement or by proprietary splice sleeves.

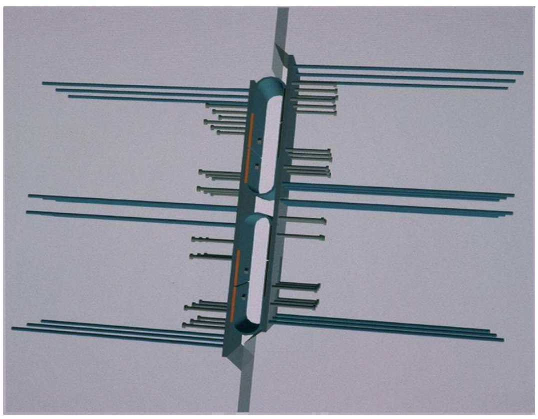

Fig. 5. U –plate connecting panels through embedded plates in adjacent panels (Ductile Connection)

Connections-General Structural Design Considerations

It cannot be stressed enough that the behavior of precast concrete systems depends on behavior of connections. General structural design considerations are:

– Strength
– Ductility

– Durability
– Fire Resistance, and
– Volume Change

Strength

The calculated strength must exceed the anticipated demand.

– The calculated strength = strength reduction factor x nominal strength
– Anticipated demand = code specified gravity and lateral loads, volume change, stability requirements x additional load factor

Ductility

Ductility can be defined as the ability to undergo large inelastic deformations prior to failure.

– In structures, it can be measured as the amount of deformation between first yield of reinforcing steel and failure
– Overall ductility of structure = ductility of structural members + ductility of connections
– Only in precast concrete structures the ductility of connections can be effectively used to provide overall ductility, however, the connection ductility is material dependent, and anchorage dependent:
  i) Connection material must be capable of undergoing large inelastic deformations. e.g. deformed bars, headed stud anchors, A36 steel shapes, welded wire fabric etc., and
  ii) Anchorage must be strong enough to prevent pull out, or avoid concrete failure

Durability

Durability can be considered to be provided when a connection does not lose its intended properties during the life of a structure.

When exposed to weather or corrosive environment, steel connection hardware must be protected. This can be achieved by: adequate concrete cover, galvanizing, epoxy coating, or using stainless steel hardware.

Fire Resistance

Connections need to be protected from fire damage to the same degree as the members they connect, to provide structural adequacy. Sometimes, interior connections do not have adequate concrete cover to provide fire resistance (Fig. 6.).

Fig. 6. Connection vulnerable to Fire

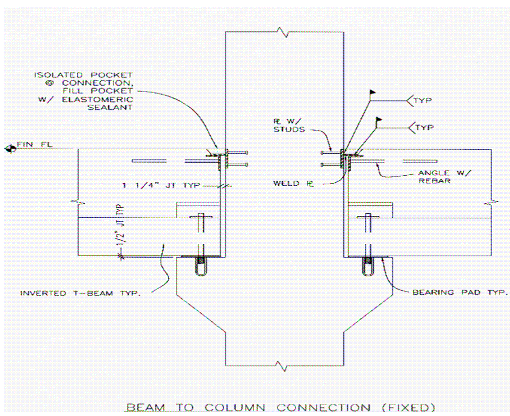

Fig. 7. Fixed connection does not allow for volume change movement

Volume Change

Many precast prestressed members are of high strength concrete and long, resulting in creep and shrinkage. Although some creep and shrinkage takes place before connections are made, not all creep is accounted for prior to connecting the members.

Temperature effects are predominant, particularly in exposed structures such as parking garages. Connections need to allow some movement of members to relieve stresses due to volume change. A type of fixed connection made for continuity (Fig. 7.) does not allow for movement.

Causes of Failures

Causes of failures are classified in two broad categories:

– Loads related.

– Capacity related.

It needs to be understood that these two causes cannot be neatly separated as reduced capacity due to any cause can initiate a failure without imposing loads beyond anticipated. A generalized equation of equilibrium can be written as:

$$C = \alpha L \tag{1}$$

where:

φ = Capacity reduction factor

C= Capacity of a member

α = Load Factor

L = Design Load

Capacity

Capacity of a member is a function of material properties and member size.

Capacity Modification factor (φ)

Capacity of a member is modified due to several factors:

– Span of the member.

– Support conditions.

– Uncertainty in material properties.

Ductile or brittle mode of failure due to material behavior under specific conditions

Capacity modification factor may vary from 0.70 to 0.90 (except under deterioration conditions). Beyond modification of theoretical capacity, a member may have reduced capacity due to deterioration of reinforcing or structural steel, fatigue loads, or repeated prior cracking. Capacity may also be reduced due to unanticipated behavior such as excessive drift, redistribution of forces and change in support conditions beyond design intention. Such situations occur in members subjected to seismic loads.

Design Loads

Design loads in building codes are based on probability of a certain intensity of load likely to be imposed on the member or a system. This applies to both dead loads and live loads, although the confidence level in dead level intensities may be high. Live loads include occupancy, wind, rain, or earthquake hazards. Live load intensities are based on probability of occurrence over a certain period (return period), e.g. 100 year floods, 500 year earthquake etc. Snow and rain are gravity types, whereas wind and earthquake loads are lateral loads although they have a vertical component negating or adding to the gravity loads.

Load Factors (α)

Since live load intensities are derived from data, uncertainties exist in data and the distribution. Load factors are used to account for uncertainty in probability of live and dead loads. Load factors vary from 1.2 to 1.7. Dynamic effects of loads are not accounted for in these load factors.

Beyond applying load factors to design loads, unusual load intensities may be imposed on members due to redistribution of loads under changed behavior in actual hazard, unanticipated loads beyond anticipated based on probabilities and unintended conditions such as short column, lack of continuity or fixity of members rather than designed flexibility.

Precast Concrete Buildings

In precast concrete buildings, the initiation of failure is almost always in the connections area. Connection as designed and as constructed and its actual behavior however, could be significantly different. Some examples of two types of most common types of precast buildings are described below: parking garages and large panel residential buildings.

Parking Garages

Parking garages constructed with precast concrete are very popular and economical. These are unique structures with double or single tees as floors supported on precast concrete columns with corbels. A thin concrete topping is used for wearing surface.

Fig. 8. A Parking Garage, Staunton, VA

The structural connection between floor members is through weld plates cast in the flanges. Failures in parking garages are known to occur due to corrosion of weld plated in flanges (due to deicing salts) of floor members, slippage of floor members from corbels due to inadequate support length, breaking of weld-plates due to unacceptable camber in adjacent members, and short column effects along parking garage ramps. Short-column effects are particularly dangerous as they could occur at any level including at garage ramps. The short- or captive-column failure occurs due to partial restraining of the columns that are, in turn, subjected to high shear stresses and fail in shear if unable to resist these stresses (Fig. 10.). Another cause of failure of parking garage is associated with inadequate gravity load – carrying capacity of non-lateral load resistance participating members such as beams and columns. An example is shown in Fig. 9.

Fig. 9. Parking garage – Northridge earthquake (1994) – inadequate capacity of non participating elements

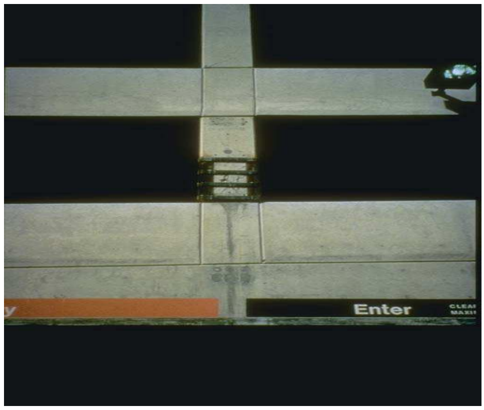

Fig. 10. Short Column failure – Northridge earthquake (1995) – Parapet walls reduced the height of columns

Residential Buildings

Perhaps the largest residential construction in post-war Europe was accomplished using large panel precast concrete construction and they are still used extensively in many eastern and northern European countries.

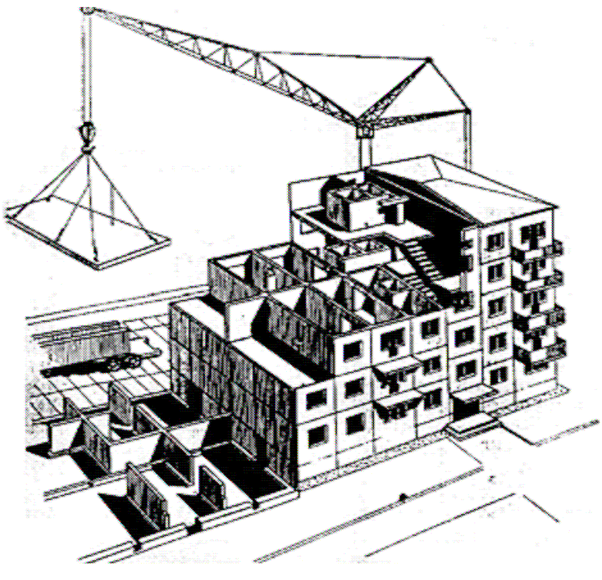

Fig. 11. A large-panel residential building (WHE Report 55, Russian Federation)

The buildings range from low-rise to high-rise. By the very nature of an apartment layout, this type of construction is shear-wall dominated. Room size panels are erected in both directions with precast concrete planks either solid or hollow-core type span the room and are supported on the walls (Figure 11). The walls behave as load bearing walls for gravity loads and as shear walls for lateral load resistance. Generally, vertical and horizontal connections are achieved by structural steel hardware, although some systems use cast- in-place concrete or grout.

Structural integrity and overall behavior of these buildings depends on the behavior of steel connecting hardware. Several large panel buildings that failed in earthquakes in Yugoslavia, USSR, Romania, Armenia, Turkey and other countries had poor connection details and inadequate capacity of connections (Fig. 12). Well designed panel buildings have performed well even in Kobe earthquake (1995) in Japan. The most famous example of failure of large – panel buildings is Ronan Point Tower (1968) in U.K. where a corner of the building collapsed due to gas explosion dislodging a panel in a corner apartment and initiating a progressive collapse of the entire building (see Fig. 13).

Fig. 12. Building collapse Spitak (Armenia) earthquake 1988 (WHE Report 66, Uzbekistan)

Fig. 13. Ronan Point Tower (16th May 1968) East London (Courtesy Google web)

In the US, these types of buildings are constructed using large spans, typically 28 to 30 ft with hollow core slabs spanning the walls. The slabs are topped with structural topping and are positively connected. Vertically many large panel buildings are post-tensioned, which serves as the panel to panel connection Fig. 14).

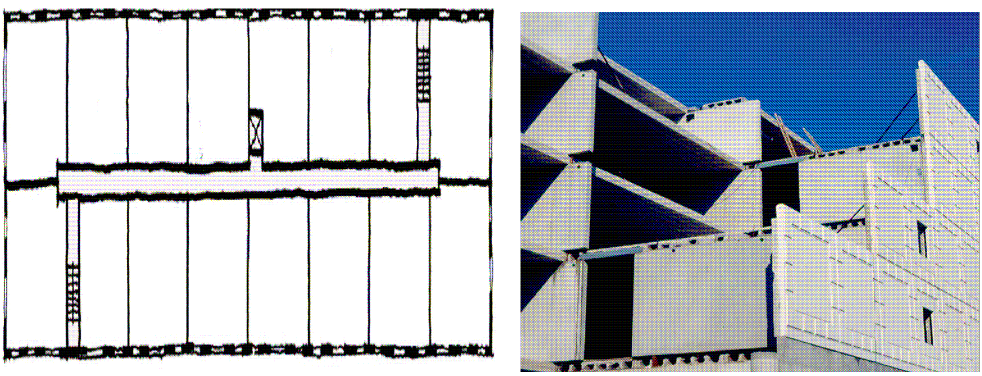

Fig. 14. Double –Loaded corridor Apartment building (Courtesy- Old Castle Co.

Continuity and Structural Integrity

To prevent failures in precast concrete buildings, it is necessary that all members must be connected positively to provide structural integrity to the entire structure. It seems obvious but unless connections are designed and constructed to provide their intended actions, unusual loads and unintended behavior occurs resulting in failures. Understanding precast concrete diaphragm is extremely important. Wall rigidities and consequent diaphragm deflection play significant part in diaphragm behavior. Assumption based on monolithic behavior may be erroneous. Most diaphragms are precast concrete large members and need to be connected to ensure that the diaphragm behaves as one unit. An example is shown in Fig. 15÷17.

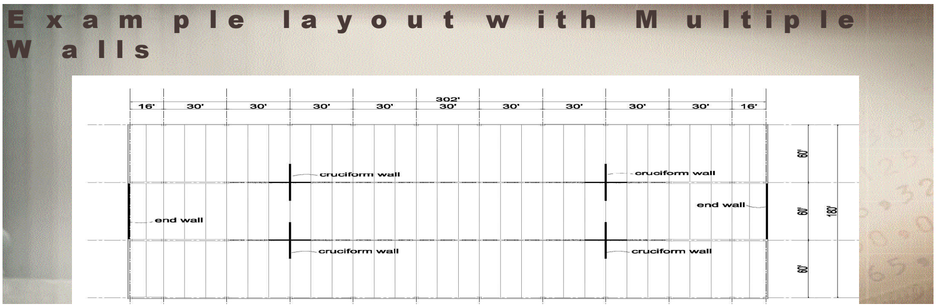

Fig. 15. Various types of Connections used in US –large panel building construction

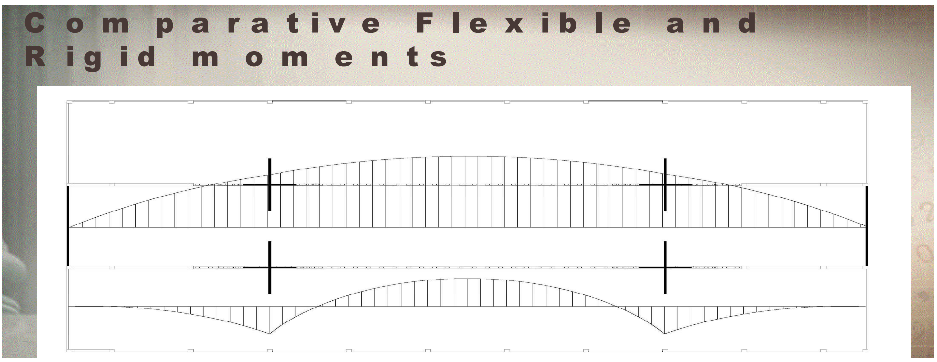

Fig. 16. Diaphragm behavior related to wall rigidities (Typical parking layout) Courtesy-Clelland

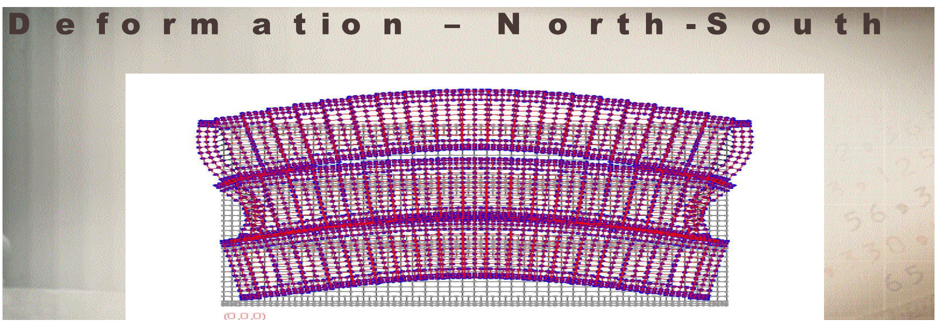

Figure 17. Finite element model of diaphragm analysis and deflection (Courtesy- Clelland)

Wall and floor members must provide continuity through positive connections. Connections between a floor member and supporting member are also very important to transfer diaphragm forces to lateral load resisting members. These require connections across the supporting member and with the supporting member. Typically, reinforcing steel protrudes out of the supporting member which is then lapped or welded to reinforcing steel of the floor member. In parking garages or long span industrial buildings, an intermediate supporting member such as a ledger beam may be required. Floor members may be solid slabs, hollow core slabs or double tees and single tees. Continuity also may be achieved without topping. Some connections that are typically used are shown in Fig. 18.

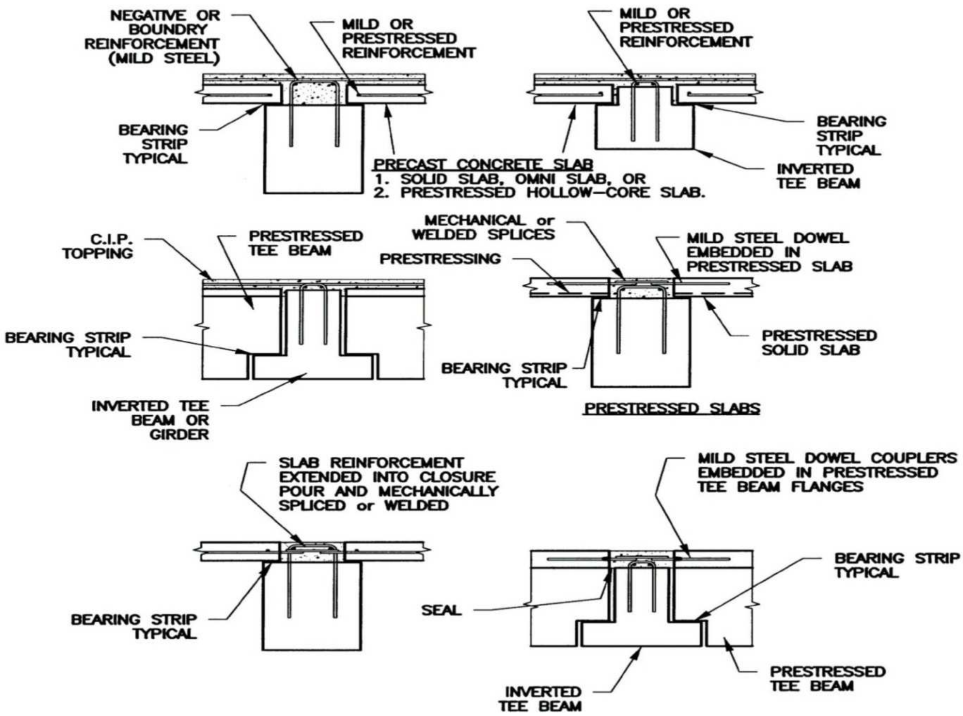

Figure 18. Floor slab and supporting member connections

In residential housing, continuity is required not only between the floor slab and the wall panels in horizontal direction but also between the wall panels in vertical direction. In the US, as noted before, story-high post-tensioning rods are used in each panel and coupled at the story level with another post-tensioning rod. However, in low-rise buildings, reinforcing steel is used which then requires either a lap splice or needs to be welded. Some examples of these are shown in figure 19.

Summary and Conclusions

Precast concrete buildings pose unique challenges in achieving intended behavior as designed because many assumptions are made in behavior of connections. The practice and codes are written to develop connections to emulate the behavior of monolithic concrete structures. The overall behavior of precast concrete buildings is primarily dependent on the behavior of connections. The deformation, rigidity, anchorage, and interaction between different materials need to be accounted for to understand the connection behavior. Many research programs have been recently undertaken for this very purpose and provide good information.

It is not important to emulate the monolithic concrete structure. What is more important is to develop the performance of the precast concrete buildings that is equivalent to monolithic concrete buildings. This performance equivalency is required at service level as well as at the ultimate load level.

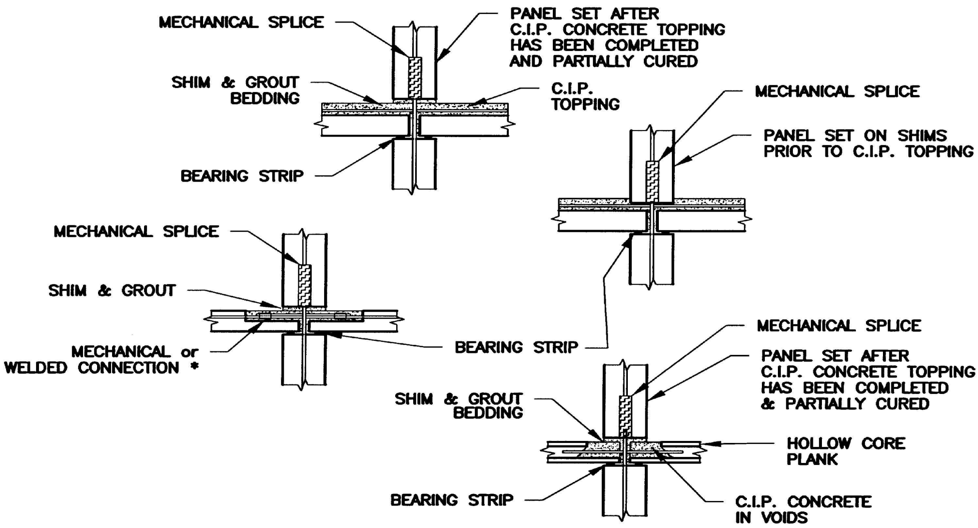

Fig. 19. Various types of continuity connections between walls and floors

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