PRECAST IN SEVERE SEISMIC ZONE: LESSONS FROM THE 27F EARTHQUAKE

Ernesto Villalobos Vildósola - Civil Engineer CHILE
Universidad Técnica Federico Santa María
General Manager Holcim Modular Solutions S.A. – Costa Rica
Chile is a seismic country by nature, so it is imperative to apply good education and preventive culture, in addition to having the necessary tools to face the collateral effects of a major earthquake, such as the one that occurred on February 27th. This earthquake (known as 27F) and its subsequent tsunami struck the central and southern regions of Chile, with the Biobío Region being particularly affected, resulting in serious damage to infrastructure, buildings, and loss of human lives.
Chile is located in the Pacific Ring of Fire, where the Nazca plate enters under the Sudamerican plate.
The 2010 earthquake (known by 27F) was an earthquake that occurred at 03:34 AM on Saturday, February 27, 2010, reaching a magnitude of 8.8 MW. It is considered the second strongest in the country's history and the eighth strongest ever recorded in the world. The epicenter was located in the Chilean Sea, off the coast of Biobío Region, at a depth of 30.1 kilometers beneath the Earth's crust. The earthquake had a maximum duration of 180 seconds in areas near the epicenter with 70 seconds of high intensity.
Seismic cycle. a) and b) Inter-seismic cycle. Deformation accumulates in the overriding plate. c) Co-seismic period, plate deformation is released.
M 8,8
Richter

Images post earthquake and tsunami.
Highway viaduct collapse - Seismic zone 3 on type 3 Soil (Expansive clay).

Displacement of the bridge deck until the collapse.
Undamaged Highway viaduct after 27F - Seismic zone 2 on type 2 Soil (Compact gravel).

Undamaged Electric train viaduct after 27F - Seismic zone 2 on type 2 Soil. 100% de

Bridges near other damaged structures, that were founded on compact soil.
PRECAST IN SEVERE SEISMIC ZONE: LESSONS FROM THE 27F EARTHQUAKE

Bridge in epicentral zone, Región del Biobío - Seismic Zone 3 on Type 3 Soil (sand).

Infrastructure liquefaction.
Highway viaducts without damages after 27F - Seismic zone 3 on type 2 Soil.

Bridges near other damaged structures, that were founded on compact soil, with better tops to avoid lateral displacement.
Highway level crossing – Beam damaged by excessive lateral displacement - Seismic zone 3 on type 3 Soil (Expansive clay).
Unmanged cross highway bridges after 27F - Seismic zone 3 on type 2 Soil.
Shear failure in deck beams. Ship labeled in seismic zone 3 and soil type 3 (soft).

Displacements over what is allowed in the standard and damage to architectural elements. Remaining deformations in foundations and structure. Seismic zone 3 and soil type 3.
Damage to non-structural and operational secondary elements.
60m span building. 12m height. Had an excellent behavior during the 27F.
Seismic zone 3 and typo 3 soil (expansive clay).
Damage and collapse in connection of roof beam in building in seismic zone 3 (high seismicity) and type 3 (soft) soil.

40m span building. 12m height. Had an excellent behavior during the 27F. Seismic zone 3 and type 3 soil (expansive clay).
Collapse of concrete facade panels.
Secondary elements.

Damage in beam to column connection.
Warehouse and process 36m span building. 8m height. Both had an excellent behavior during the 27F. Seismic zone 3 and typo 3 soil (expansive clay).
PRECAST IN SEVERE SEISMIC ZONE: LESSONS FROM THE 27F EARTHQUAKE

Building collapse in epicentral area, Biobío region. Seismic Zone 3 y type 3 soil, sand.
Building collapse in epicentral area, Biobío region. Seismic zone 3 and soil type 3, sand. A similar building can be seen next to the building, without damage.
Types of repetitive damage in mid-rise buildings in the epicentral area. Concentration of compressive stress in singularities and concentration of shear stress in lintels of coupled walls are a recurring failure.
Shear failures and high flexocompression stresses caused loss of the concrete core and buckling of the main reinforcement.
Shear failures and high flexocompression stresses caused loss of the concrete core and buckling of the main reinforcement.
The area affected by the 27F earthquake was 500 km.

In the 27F earthquake, 95% of deaths were caused by the tsunami.

In 27F no deaths are associated with prefabricated concrete structures.
The earthquake had a cost of 30 billion dollars for Chile, which is 18% of the Gross Product.
Between 10% and 30% of the building was damaged. Of all the buildings in the affected area, only 2 collapsed.

Within these, of the entire surface area of precast concrete structures (app 1.5 million m²), only 1.7% suffered serious damage and collapse.
The largest number of buildings with severe damage are between 4 and 8 stories.
Accelerogram measured in compact granular soil - Type 2 soil.

Seismic design standard.

Spectral response in compact granular soil. 3-coordinates.
Accelerogram measured in soft clayey soil - Type 3 soil.

Spectral response in soft clayey.

Seismic design standard.
PRECAST IN SEVERE SEISMIC ZONE: LESSONS FROM THE 27F EARTHQUAKE

Effects of soil type on the seismic wave

- Rock
- Soft soils

Wave amplification

Effects of soil type on the seismic wave
Macro seismic Zones in Chile

<table>
<thead>
<tr>
<th>Zone sismica</th>
<th>$A_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.20 g</td>
</tr>
<tr>
<td>2</td>
<td>0.30 g</td>
</tr>
<tr>
<td>3</td>
<td>0.40 g</td>
</tr>
</tbody>
</table>
Seismic Microzoning

Topographic effects

Amplification

Liquefaction. dynamic compaction Glide.

Fall rocks

Failure

Epicenter

Stratigraphic effects

Effects of different morphologies that amplify the seismic wave.
Response of precast concrete typical structures.

<table>
<thead>
<tr>
<th>Height [mt]</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.97</td>
<td>0.98</td>
<td>1.01</td>
<td>1.04</td>
<td>1.07</td>
<td>1.10</td>
<td>1.12</td>
<td>90x90</td>
<td>80x80</td>
</tr>
<tr>
<td></td>
<td>1.05</td>
<td>1.06</td>
<td>1.09</td>
<td>1.13</td>
<td>1.17</td>
<td>1.19</td>
<td>1.22</td>
<td>80x80</td>
<td>70x70</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>0.92</td>
<td>0.95</td>
<td>0.98</td>
<td>1.02</td>
<td>1.04</td>
<td>1.06</td>
<td>70x70</td>
<td>60x60</td>
</tr>
<tr>
<td></td>
<td>0.99</td>
<td>1.01</td>
<td>1.04</td>
<td>1.08</td>
<td>1.12</td>
<td>1.15</td>
<td>1.17</td>
<td>70x70</td>
<td>60x60</td>
</tr>
<tr>
<td></td>
<td>0.84</td>
<td>0.85</td>
<td>0.88</td>
<td>0.91</td>
<td>0.95</td>
<td>0.97</td>
<td>0.99</td>
<td>60x60</td>
<td>60x50</td>
</tr>
<tr>
<td></td>
<td>0.94</td>
<td>0.95</td>
<td>0.98</td>
<td>1.02</td>
<td>1.06</td>
<td>1.09</td>
<td>1.12</td>
<td>60x50</td>
<td>50x50</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>0.77</td>
<td>0.80</td>
<td>0.83</td>
<td>0.86</td>
<td>0.89</td>
<td>0.91</td>
<td>50x50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.85</td>
<td>0.87</td>
<td>0.90</td>
<td>0.93</td>
<td>0.97</td>
<td>1.00</td>
<td>0.94</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>0.66</td>
<td>0.68</td>
<td>0.71</td>
<td>0.74</td>
<td>0.76</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

240 256 288 336 384 420 450
20 x 12 16 x 16 24 x 12 28 x 12 24 x 16 35 x 12 30 x 15

**Colaborating Area [m2]**

**Grid [mt x mt]**
The Fundamental Period $T^*$ of prefabricated buildings with rigid connections, slabs and shear walls is in the range of 0.4 to 0.7 [sec].

The Fundamental Period of warehousing with cantilever columns is in the range of 0.7 to 1.3 [sec].
Desing with the chilean code NCh 2369of2003 $\xi=2\%$, $R=3$.

Desing with the chilean code NCh 2369of2003 $\xi=3\%$, $R=5$.

Desing Spetrum (Lateral force)

$$S_a = \frac{2.75 A_o I (T')^n}{R} \left(\frac{0.05}{\xi}\right)^{0.4}$$

Maximum lateral deformation

$$d_{\text{max}} = 0.015 h$$

Slenderness limitation in columns $\lambda = k \frac{L}{r} \leq 100$
Chilean Seismic Codes Modified Design Spectrum after 27F

One of the first measures after the earthquake was to increase the design forces in high seismicity areas and soft soils.

Rock soils

Compact soils

Soft soils
Review of concepts and designs by element and connection.
Current codes and regulations for design in Chile:

a) NCh 2369 Of. 03: Diseño Sísmico de Estructuras e Instalaciones Industriales.
b) NCh 433 Of. 09: Diseño Sísmico de edificios.
d) NCh 1537 Of - 2009: Cargas Permanentes y Sobrecargas de Uso.
e) NCh 432 Of.2010: Cálculo de la acción del viento sobre las construcciones.
f) NCh 431 of.2010: Construcción, Sobrecargas de nieve.
g) NCh 3171 of.2010: Disposiciones generales y combinaciones de carga.

f) ACI 318-14: Requisitos de Reglamento para Concreto Estructural y Comentarios. Load and Resistance Factor Design method (LRFD)

g) Decreto supremo N°60, Reglamento que fija los requisitos de diseño y cálculo para el hormigón armado.
h) Decreto supremo N°61, Reglamento que fija el diseño sísmico de edificios.
i) Ordenanza general de Urbanismo y Construcción.
j) PCI design handbook.
l) EHE - 08: Instrucción Española de Hormigón Armado.
m) EP - 93: Instrucción Española de Hormigón Pretensado.

k) EF - 96: Instrucción Española de Forjados Unidireccionales.
Column connection to foundation.

Critical zone in all industrial precast concrete structures. His work in flexion was intense and required increasing his confinement to increase ductility at the base.
The design criteria are:

\[ Z = 0.9 \ E \]

Angle: \( \beta ^{\circ} \)

\[ F_{s1} = (M/0.9E) + (H \times 0.9) \]

\[ F_{s2} = (M/0.9E) + H \]

\[ Tg \ \beta = \frac{0.9xE}{0.85L-t/2} \]

\[ F_{v1} = F_{s1} \times Tg \ \beta \]

\[ F_{v2} = F_{s2} \times Tg \ \beta \]

In the design of the foundations it is required that at least 80% of the area is in compression.

The walls of the chalice are smooth and the filling is done with H-35 concrete with an expander and fluidizer, maximum size of the aggregate: 10 mm.

The behavior of these joints has been excellent and not a single failure, no relative movement or tearing has been detected, so the solution with smooth walls and depth 1.5 times the width of the column has proven to be ideal in severe seismic conditions.
Column connection to foundation.

A.1. Empotramiento de columna en vaso o cáliz interior.

The design criteria are:

- **E = 1.5 C**
- Horizontal traction force : \( T_{cer} = (\mu + H_u \times E)/Z \)
- \( Z = 0.9 \times E \) Angle : 45°
- Vertical traction force : \( T_{ver} = T_{cer} \)
- Diagonal compression force : \( F_c = 1.4 \times T_{cer} \)

In the design of the foundations it is required that at least 80% of the area is in compression.

The behavior of these joints has been excellent.
**Column connection to foundation.**

Embedment by means of waiting reinforcements inserted into corrugates pods and filled with grout mortar.

The behavior of these joints has been excellent.
In addition to obtaining the main reinforcement, the requirements of the ACI-318 standard related to seismic designs must be followed.

Fig. 3.4 Confinement of column sections by transverse and longitudinal reinforcement.
The compressive strength increased approximately 1.6 times and the maximum deformation 4.5 times.
PRECAST IN SEVERE SEISMIC ZONE: LESSONS FROM THE 27F EARTHQUAKE

Flexural hysteresis cycle of a confined concrete section.

Fig. 4.77 Seismic response of a diagonally reinforced spandrel beam.

This is the ideal ductile behavior of a section of the structure in an earthquake.
Confinement or ductility demand in columns.

Rigids connections. Moment connections.

Confinement or ductility demand in columns and beams.
Articulated connection between beam and columns.

Its fundamental mission is to transmit the horizontal forces (seismic mass) from roof to column even under extreme cyclical stresses.

The sizing of the pins must meet 3 conditions:

Let $V_u$ be the factored seismic shear to be transmitted through the patella.

1. Pure shear of the dowel bars: $V_u < 0.5 \times A_s \times f_y$
2. Concrete crushing against the bars: $V_u < \Phi V_n = V_{nc} = \sqrt{f'c} \times \sqrt[3]{d} \times (8.5 L_b + 7.5 \Phi + 150)$ taken $L_b \leq$ edge distance
3. Near edge failure (conical break): $V_u < \Phi V_n = V_{nc} = 3.5 \times m^{1.5} \times \sqrt{f'c}$

This connection is recommended for low-rise buildings, median seismic zones and compact soils. This is because there are often large deformations that override the requirement of the code and the only way to compile the code is to increase the section of the columns and funds.
Articulated connection between beam and columns.

Articulated roof beam with a double T section joined to the column in its lower wing by means of 2 projecting reinforcements awaiting the pillar and holes in the beam, filled with grout on site.

This connection did not find good behavior in the earthquake due to the concentration of tensions and little space to have armor.
Articulated connection between beam and columns.

Articulated beam with an extreme rectangular section, joined to the column by means of 2 salient pins in the edge of the column and holes in beam, filled with grout.

This connection had a optimal behavior in the 27F earthquake in medium seismic zones and compact soils. The rectangular end allowed a good distribution of tensions and placement of the confined steel.
Rigid connection between beam and columns.

Roof beam connected through salient armaduras in hopes of both positives and negatives, interspersed with hopes of pilar, framework and in situ concrete (Wet Connection).

This connection had a very good performance during the 27F earthquake. In the buildings where it was used, deformations were very well controlled, even in strong seismic zones and on soft soils.
PRECAST IN SEVERE SEISMIC ZONE: LESSONS FROM THE 27F EARTHQUAKE

Rigid connection between beam and columns.
Rigid connection between beam and columns.

View of the detailing of the shear and confinement reinforcement at the node.
Rigid connection between beam and columns.

Undamaged structures after 27F. Seismic zone 3 and Soil type 3 (soft soil). The rigid connection between column and beam had an excellent behavior on deformation control.
Rigid connection between beam and columns.

Only crack observed in this type of connection during the 27F earthquake.
Connection between dalla roof beam and beams.

1. Roof beam connection fixed through 2 or 3 holes and pins placed and grouted on-site.
2. $F_u < 2 \Phi A_s f_y$

This connection did not perform well in 27F due to construction execution errors.
Connection between dalla roof beam and beams.

1. Connection a protuding bars from the beam.
2. $F_u < 2 \Phi A_s f_y$

This connection performed well during the 27F earthquake. There were no observed crushing failures.
Rigid connection between the roof beam and beam

Connection a protuding bars from the roof beam, stirrups protruding from the beam and on site bars, all joined with high resistance mortar.
Rigid connection between della roof beam and beam

The embedded connection was designed to make use of the width of the roof beam in order to create a Vierendeel-type beam between the roof beams and the beam in the roof plane, as these are capable of resisting moments in the horizontal plane. Under gravitational load, the flange still acts as a simply supported beam.

With this configuration, a flexible horizontal diaphragm is formed, ensuring the bracing of the structure in its roof plane, distributing seismic loads across all columns.
Rigid connection between the roof beam and beam

Laboratory tests of the connection demonstrated its excellent energy dissipation capacity throughout its hysteresis cycle. Buildings with this system experienced much less deformation, as evidenced by minimal damage to non-structural elements.
Rigid connection between a roof beam and a beam.

Buildings with this connection distributed seismic forces more effectively.
Rigid connection between the roof beam and beam

Buildings with this connection distributed seismic forces more effectively
**Rigid connection between “T” roof beam and beam**

Connection a protruding bars from the beam.

$$F_u < \Phi A_f y$$

Buildings with this type of T roof beams require a robust roof bracing system to distribute seismic forces. This element had a good behavior in 27F.
Connection between “H” edge beam and beam

Articulated connection through 2 holes with protuding and one on site drilling pins and grouted on-site.
Connection between “H” edge beam and beam

Edge roof beams shaped like an H-beam have four functions:

1. Purlin beam connecting column heads.
2. Channeling and drainage of water.
3. Roof support as an edge flange.
4. In some cases, attachment of large-format enclosure panels.

This edge beam serves multiple functions in the structure and operation of the roof. In some cases, concrete panels were supported on this beam, resulting in damage to their attachment and localized collapse.
Connection between “H” edge beam and beam

The tremendous seismic forces transmitted by the panels have occasionally caused damage to these fastenings.

It is not advisable to assign multiple functions to an element that will be subjected to significant seismic loads. The H-beam is not designed to withstand the significant seismic forces from concrete cladding panels. It is better to specify stronger beams for this purpose.
Bracing system with high-strength cables

Bracing using high-strength cables working exclusively in tension.
Bracing system with high-strength cables

This system exhibited acceptable performance during the 27F earthquake. Elongation was observed in the tensioners, indicating the big demand. They distributed the horizontal forces effectively.

The vast majority have become slack, and it has only been necessary to re-tension them to put them back into service.
Bracing system with steel tubular profiles

Bracing with a steel tubular profile capable of working in compression and tension.
This tension-compression system with steel profiles did not exhibit acceptable performance during the earthquake. Its stiffness and strength higher than concrete, resulted in localized damage at the junction with the concrete element.
Hollow core slabs: diaphragm

Hollow core slabs with a structural topping forming a floor diaphragm.

It was observed that the system was capable of transferring floor loads to the columns through the beams. In cases with shear walls, the diaphragms with hollow core slabs and structural topping showed similar cracking to in-situ slabs. Special care should be taken not to exceed the permissible inter-story deformations of the seismic code to avoid problems in the support of the slabs on the beams.
Hollow core slabs: diaphragm

Building with prefabricated concrete columns, beams, slabs and in-situ shear walls, that performed well during the 27F earthquake.
CONCLUSIONS

- The prefabricated concrete structures exhibited satisfactory performance during the 27F earthquake. 1.7% of 1.5 MMm2 had damage or collapse, without human losses.

- Simplicity is security in the structure.

- Properly estimating and limiting deformations.

- Design with ductile elements.

- In buildings with shear walls, reduce compressive forces and increase edge confinement.

- Avoiding brittle shear failures and stress concentration.

- The study of the local seismological conditions, soil and definition of the type of behavior expected will be key elements in the resistance of the building.
Thank you very much for your kind attention.

Any question, please send to:

ernesto.villalobos@hms.holcim.com

Whatsapp +506 63032180