Part 4: Post Earthquake Damage Evaluation and Retrofitting of Reinforced Concrete Buildings
Why do the repair and retrofitting of earthquake damaged buildings essential?

The occurrence of earthquake leaves behind innumerable damaged structures with varying intensities ranging from minor cracking to total collapse. At such a moment replacement is neither feasible nor practical to meet out shelter problems. Therefore, repair and retrofitting is the only solution which may convert such buildings to seismically safe structures for future earthquakes. This section of the manual intends to provide guidance for repair and retrofitting of earthquake damaged structures.

Typical damages in a RC buildings

![Diaphragm distress](image)

- Cracked infill wall (with cracks extending through concrete frame)
- Racking of cladding connections
- Damaged cladding connections
- Columns out of plumb (at any level)
- Column concrete spalling
- Panel zone cracking
- Beam concrete spalling exposure of reinforcement

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What are the causes of column failure in an RC building and in what manner?

Columns are damaged mainly due to lack of confinement, large tie spacing, insufficient splices length, inadequate splicing at the same section, hook configurations, poor concrete quality, less than full height masonry infill partitions, and combinations of many of the above compounded with vertical and geometrical irregularities. Failure of columns has catastrophic consequences for a structure. Two types of failure in columns are generally observed as shown below and their consequences are also listed.

**Failure sketch**

Type 1: Damage at the top and bottom section of column (often occurs in long columns)

Type 2: Damage in weakest part of column in the form of X-shaped cracks (often occurs in short columns)

**Consequences of damage**

- Loses its ability to carry vertical load
- Spectacular collapse of the building
- Generally occurs in columns of ground floor
- Loss of equilibrium
What is the cause of beam failure in a building and in what manner?

Only a few examples exist in which buildings have exhibited plastic hinging in the beam. The probable regions of hinging are at and near their intersections with supporting columns. The causes of hinging are lack of confinement of concrete core and support for the longitudinal compressive reinforcement against inelastic buckling.

**Failure sketch**

Type 1: Orthogonal to beam axis along the tension zone of the span

Type 2: Shear failure near the supports of beam

**Consequences of damage**

- Most common type of damage
- Existing micro cracks, due to bending of the tension zone, widened due to vertical component of earthquake.
- Does not jeopardize the safety of structure

- Second most frequent type of damage
- More serious than the previous one
- Brittle in character
- Sometimes jeopardize the overall stability of the structure

**Failure sketch**

Type 3: Flexural cracks on the upper and lower face of beam at the supports

Type 4: Shear failure at the location of indirect support/secondary beams

**Consequences of damage**

- Flexural cracks on the upper and lower face of the beam
- Cracking at lower face due to bad anchorage of the bottom reinforcement in to the support, in that case one or two cracks from close to support

- Due to the vertical components of earthquake which amplified the concentrated load
What is the cause of beam-column joint failure in a building and in what manner?

Beam-column joints are critical elements in frame structures, are subjected to high shear and bond-slip deformations under earthquake loading. Account for cross-sectional properties of the joint region, amount and distribution of column vertical steel, inadequate or absence of reinforcement in beam-column joints, absence of confinement of hoop reinforcement, inappropriate location of bar splices in columns are the common causes of failure of beam-column joints.

Failure sketch

![Failure sketches](image_url)

**Type 1: Corner Joint**

**Type 1: Exterior Joint**

**Type 3: Cross shaped Joint**

Consequences of damage

Reduce the overall stiffness of the building
What is the cause of slab failure in a building and in what manner?

Generally slab on beams perform well during earthquakes and are not dangerous but cracks in slab create serious aesthetic and functional problems. It reduces the available strength, stiffness and energy dissipation capacity of building. In flat slab construction, punching shear is the primary cause of failure.

**Failure Sketch**

Type 1: Cracks parallel or transverse to the reinforcement at random locations

Type 2: Cracks at critical sections of large spans or large cantilevers, transverse to the main reinforcement

**Consequences of damage**

- Most of time it is due to the widening of already existing micro-cracks due to bending action/temperature changes/shrinkage. It became visible after dynamic excitation.
- Sometimes due to differential settlement of columns.

**Failure Sketch**

Type 3: Crack at locations of floor discontinuities, such as the corner of large openings accommodating interval stairways, light shaft and so on

Type 4: Cracks in areas of concentration of large seismic load effects, particularly in the connection zones of slab to shear walls or to column in flat plate system

**Consequences of damage**

- Mostly due to the vertical component of the earthquake action
- Punching shear failure
- Aggregated by the cyclic bending moment caused by an earthquake
- Slab directly on column seismically vulnerable structures. It should be avoided.
What is the cause of shear wall failure in a building and in what manner?

Shear wall generally performs well, but sometimes shows diagonal flexural-shear cracking causing significant damage to coupling beams and short piers between openings.

Failure Sketch

Type 1: X-shaped shear cracks - limited spelling
Type 2: Sliding at the construction joint
Type 3: Damage due to flexure and compression

Consequences of damage

- Under the action of vertical loads, the isosceles triangles formed on the two sides tend to separate from the structure and therefore cause of collapse.
- Most frequent type of failure.
- Old concrete is not properly bounded with fresh concrete.
- Not too serious because the structure still carries vertical load.
- Very rarely occurs because of bending moment developed at the base of the wall much smaller when those calculated for the design.
What is the cause of infill failure in a building and in what manner?

Infill wall failure occurs due to stiffening effect of infill panels because of i) unequal distribution of lateral forces in the different frames of a building - overstressing of some frames ii) vertical irregularities in strength and stiffness - soft storey iii) horizontal irregularities - torsion and iv) failure of infill itself.

Mode of failure of in-filled masonry in RC moment resisting building frame
Why is repair necessary before retrofitting of earthquake damaged structure?

The aim of repair is to reestablish the initial strength of damaged structural members. Properly repaired structural members may possess the same strength but will have a somewhat reduced stiffness due to very fine cracks. Retrofitting is the judicious modification of the strength and/or stiffness of structural members and improve structural performance. Retrofitting will be effective when the damaged structures have sufficient strength and stiffness achieved by the repairing process. The choice of repair depends upon post earthquake evaluation besides other minor factors such as local site conditions, type and age of the structure, type and degree of damage, available time, equipment and staff for specific architectural requirements, cost, and the required level of seismic safety.
What should be the aim of post earthquake damage evaluations?

Post earthquake investigation is the statement of the structure pertaining to its nature and degree of damage, design and emergency measure for temporary support to minimize the possible material loss in case of increased damage to structure during aftershocks. The post damage evaluation is also utilized in determining repair and/or retrofitting measures.

It is an evaluation of the structure which may require removal of some non-structural components, coatings, concrete covers, details of cracks, yielded reinforcement, excessive deformations, connection failures, etc. It is also an assessment of the structural members to resist the seismic forces and the dead and live loads\(^\text{26}\).
What are the considerations for emergency measures in temporary protection?

Temporary protection provides temporary strength or support for damaged elements and connections to achieve safety of the whole structural system. Temporary support is recommended for severely damaged buildings which exhibit in the form of a rupture of a column, serious cracking of load bearing walls, etc. Shoring of the damaged elements relieving danger of collapse during aftershocks is diminished. Support is needed at the floor of the damaged vertical element which may be extended to other floors as well. The purpose is to provide safety to the people in adjacent streets, sidewalks and yards; to workmen making repairs and retrofitting provisions. The distance between the supports and the damaged member must be minimum providing enough unobstructed space for the eventual repair work or replacement of damaged elements. Against unstable horizontal forces, lateral counter forts or wall braces should be provided for walls which may fall laterally. Diagonal braces of structural frames can be installed. The whole procedure should be properly organized, in order to minimize the working time of people in and under the structure.

Temporary Protection of a damaged column
What are the methods for supporting vertical loads?

A suitable method of supporting vertical load can be support of damaged or failed members with techniques such as industrial scaffolding; tree logs, steel profiles, or grillage logging\textsuperscript{26}. This depends on means, seriousness of damage and size of structure.

**Industrial-Type Shoring and Scaffolding**
For small loads, independent industrial-type metal tube shores
For shoring of beams or slabs - dismountable type metal towers, wedged to the surface with the aid of special screw type bolts.

**Timbers, Tree Logs and Telephone Poles**
For one damaged column - Minimum one 250 mm diameter log on each side
For two or more supporting elements - X-shaped braces may be preferred

**Built-up steel members or Steel Profiles**
In the same manner as in case of tree logs. Steel sections require bearing plates of both sections top and bottom and must be properly wedged. Steel profiles assembled around the perimeter of a damaged column similar to permanent jacketing can also be utilized for temporary support

**Timber Grillages**
If wooden rail sleepers or other similar timber is available, vertical support can be erected by forming a grillage. The sleepers are placed in alternating layers to the required height. On top of the grillage wide flanges steel I-beams or suitable timbers are placed
What are the methods for providing lateral support?

A suitable method of supporting lateral support of damaged walls or failed members are such as lateral wall bracing, frame bracing, wedging techniques etc.

**Lateral Wall Bracing**
Lateral wall bracing like timbers, logs or steel profiles may be used to support the hazardous/damaged/instable exterior bearing walls of masonry, stone or concrete block construction since the walls may fall outward due to the loss of vertical support.

**Frame Bracing**
For concrete framed structures, without in-filled walls in the lower story or with heavily damaged in-filled walls in a particular story; internal diagonal frame bracing can be used. Frame bracing consists of timbers, tree or steel profiles of sufficient strength for buckling. The bracing members are installed diagonally between columns on a frame line, consisting of several more slender elements laced together to form a built-up compression member. The location of the braces should be provided in a balanced system.

**Wedging Techniques**
Wedging is recommended for all temporary supports to transfer the loads from the damaged member to the new support system for which several methods may be used, such as ordinary wooden wedges with suitable securing devices, mechanical jacks, hydraulic jacks or hydraulic flat jacks to ensure uniform loading and unloading.
How to carry out retrofitting process for a damaged building?

Following steps are generally followed while carrying out retrofitting of a damaged building during an earthquake:

<table>
<thead>
<tr>
<th>Step</th>
<th>Action required</th>
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<tbody>
<tr>
<td>1.</td>
<td>Fix emergency measures for temporary protection</td>
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<tr>
<td>2.</td>
<td>Detailed documentation such as design calculations, drawings, specifications, construction details, original construction data, material strengths, foundation and soil condition data, previous repairs or alterations, codes followed etc.</td>
</tr>
<tr>
<td>3.</td>
<td>Visually inspect each and every structural member such as, beam, column, beam-column joints, staircase, floor slabs and the connections between floors and walls and foundations and note the location and amount of damage. The reason of failure should be highlighted like shear, compression, tension, flexure, bar anchorage, etc.</td>
</tr>
<tr>
<td>4.</td>
<td>Prepare the plan or alternative schemes to repair and /or retrofitting/strengthening the structure with cause of damage underlined such as discontinuities in strength or stiffness, torsion, hammering with adjacent structures, improper connections or details, effects of non-structural elements.</td>
</tr>
<tr>
<td>5.</td>
<td>Try to estimate the existing strength and stiffness of the damaged structure and with the repair and /or strengthening schemes. Precaution must be taken that the strengthening/retrofitting elements should not cause increased damage in a future earthquake. For example, If shear walls are added, new foundations will be required not only to support the weight of the wall but particularly the overturning forces otherwise it is fatal in itself</td>
</tr>
<tr>
<td>6.</td>
<td>Finalize the schemes as per feasibility, imagination and ingenuity with professional experience best with economy</td>
</tr>
<tr>
<td>7.</td>
<td>Finally design procedures include a completion of the detailed calculations of the strengthening/retrofitting solution and the preparation of drawings, specifications and instructions of the work</td>
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</table>
What type of materials can be used in Repair and Retrofitting Project?

Different types of materials may be used in repairing and retrofitting structures. Before utilizing any of these materials or techniques, the designer should study technical literatures, obtain advice, and be thoroughly familiar with the process. The most common type of materials used in repair and retrofitting are:

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional cast-in-place concrete</td>
<td>Low shrink concrete with higher strength than existing is recommended ($f_{c \text{ rep}} \geq f_{c \text{ exist}} + 5 \text{ MPa}$).</td>
</tr>
<tr>
<td>High strength concrete</td>
<td>Conventional concrete with super plasticizers and expansive admixtures in the appropriate proportions</td>
</tr>
<tr>
<td>Shotcrete (Gnite)</td>
<td>Dry mix concrete of higher strength than existing is recommended ($f_{c \text{ rep}} \geq f_{c \text{ exist}} + 5 \text{ MPa}$).</td>
</tr>
<tr>
<td>Polymer concrete</td>
<td>Polymer-modified concrete has mainly two advantages (i) water-reducing plasticizers, (ii) improving the bond between old and new elements but several disadvantages like vulnerability to fire and lower alkalinity present inferior resistance against carbonation compared to conventional concrete</td>
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<tr>
<td>Resins</td>
<td>Resins are used for grouting injections into cracks in order to glue together the cracked concrete or thin metal sheets on concrete surfaces. Its modulus of elasticity must be compatible to the concrete to be glued and viscosity appropriate for the crack width. Resins lose their strength in temperatures higher than 100°C and therefore such repairs are not fireproof. Epoxy resins are the most common type of materials in use today</td>
</tr>
<tr>
<td>Grouts</td>
<td>Grouts consist of cement, water, sand, plasticizers and expansive admixtures used for the filling of voids or cracks with large openings on masonry or concrete.</td>
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<tr>
<td>Gluing metal sheets on concrete</td>
<td>Stainless steel sheets usually 1.00-1.50 mm thick covering with an epoxy resin layer</td>
</tr>
<tr>
<td>Welding of new reinforcement</td>
<td>Low-alloy steel is preferred as new reinforcement because it may be welded more easily. New bars are welded on the old ones with the aid of connecting bars</td>
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<tr>
<td>Gluing Fiber-Reinforced Plastic (FRP) sheets on concrete</td>
<td>Similar to steel sheets fiber reinforced plastic sheets (glass, aramid and carbon fibers) are glued to structural members. Where dead weight, space or time restrictions exist, FRP are an attractive choice. But exposures can result in the weakening of the interface between FRP composites and concrete.</td>
</tr>
</tbody>
</table>
How to repair minor/ moderate cracking in a structural member?

The process of repairing is similar to all structural members i.e. column, beam, beam-column joints; shear wall etc. as it depends on crack width. There are few instances and its repairing techniques are given here:

<table>
<thead>
<tr>
<th>Post-earthquake condition of structural member</th>
<th>Repairing Technique(s)</th>
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<tbody>
<tr>
<td>Minor cracking</td>
<td>Epoxy resin injection from bottom proceeds upward through ports placed in drilled holes, spaced 20 to 100 cm</td>
</tr>
<tr>
<td>Moderate cracking</td>
<td>Cement grout injections from bottom proceeds upward through ports in drilled holes. Strength and compactness should be checked through appropriate testing.</td>
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</tbody>
</table>

![Diagram of minor cracking repair](image1)

1 - cracks; 2 - injection ports

Repairing process for minor cracking

![Diagram of moderate cracking repair](image2)

1 - existing reinforcement; 2 - added new reinforcement; 3 - added new ties; 4 - existing concrete; 5 - new concrete; 6 - welding; 7 - temporary castform

Repairing process for moderate cracking
How to repair severe cracking in a structural member?

Heavily damaged or crushed concrete

Replace with non-shrinkage concrete or concrete with low shrinkage properties. The temporary form and concrete should be higher than the finally required top level in order to compact the concrete sufficiently. After one day, the form can be removed and the fresh concrete that is beyond the normal configuration can be chipped away.

Buckling of longitudinal reinforcement, ruptured ties and crushed concrete

Totally remove and replace the damaged parts, cut the buckled reinforcement and straighten, insert new longitudinal reinforcement and weld it to the existing reinforcement, insert new additional close ties in two piece welded to each other, place the new non-shrinkage concrete. Special attention must be paid to achieve good bond between the new and the existing concrete.

Repairing process for severe cracking

1 - existing non-damaged concrete; 2 - existing damaged concrete; 3 - new concrete; 4 - buckled reinforcement; 5 - new reinforcement; 6 - new ties; 7 - welding; 8 - existing ties; 9 - existing reinforcement
Are the repairing techniques sufficient for a building in case of future earthquake?

Any repairing process is only helpful to retain the most original strength of any building. It is not helpful to increase beyond the original strength. Therefore, opt retrofitting techniques as explained in Part IV to increase its strength globally and locally wherever it is deficient.