Guideline for Seismic Upgrading of Building Structures

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Guideline for Seismic Upgrading of Building Structures
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Guideline for Seismic Upgrading of Building Structures

Preface

Summary

This Guideline provides information and advice on the seismic upgrading of existing building structures, and is intended for use by qualified structural engineers. It is a companion document to the recently published Guidelines for Seismic Evaluation of Existing Buildings and the Manual for Screening of Buildings for Seismic Investigation, both of which are related to the National Building Code of Canada. The Guideline describes conventional techniques of seismic upgrading of building structures and discusses their relative merits based on the objectives of seismic upgrading and the principal considerations in their choice and design. It also describes innovative seismic upgrading techniques such as supplementary damping and contains references to more detailed information on such techniques. It does not include techniques for upgrading of non-structural building components.

Background

This Guideline is based in part on NEHRP Handbook of Techniques for Seismic Rehabilitation of Existing Buildings, but the material has been reorganized and shortened considerably. Also, this document contains more guidance on innovative techniques than does the NEHRP Handbook.

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Chapter 1

Introduction

1.1 Purpose of the Guideline

Many buildings in seismic areas across Canada were built before there was an adequate understanding of earthquake resistance. Many of these buildings would be deemed unsafe by current building codes. Also, because code requirements are written for the design of new buildings and not for the evaluation of existing buildings, the cost of upgrading an existing building to the current code can be very large, as well as destructive to its heritage value. A set of alternate procedures for evaluating existing buildings was therefore prepared by NRC and published in the Guidelines for Seismic Evaluation of Existing Buildings (hereafter referred to as "Guidelines for Seismic Evaluation").

This new Guideline was prepared to help engineers design the seismic upgrading using appropriate techniques for correcting the seismic deficiencies identified using the above NRC evaluation guidelines. The techniques described herein include conventional methods that were employed in the past, as well as recently developed special procedures, such as supplementary damping and base isolation. The document discusses the relative merits of the various techniques, based on earthquake engineering principles, observed seismic performance, construction procedures, and costs.

1.2 Scope and Limitations

This document provides descriptions and discusses the relative merits of various techniques for seismic upgrading of buildings found by evaluation to be seismically deficient. It is not intended for the repair of seismically damaged buildings, although some of the techniques may be useful for such repairs. The techniques are described generically, accompanied by sketches to illustrate concepts. This document does not provide specific design criteria or specific details suitable for direct application, nor does it recommend specific devices.

1.3 How to Use the Guideline

The Guideline should first be read from the beginning. Afterwards it may be convenient to begin with Appendix A, which contains checklist tables of upgrading techniques, one table for each major structural system. These techniques are described in more detail in Chapters 4 to 6, identified by the appropriate page and figure numbers in the Appendix A checklist tables. The relative merits of each technique are based on objectives and principles involved in seismic upgrading described in Chapter 3. Chapter 2 reviews the types of seismic deficiencies found in existing buildings.

The design of upgrading of existing buildings involves a greater number of uncertainties and constraints than the design of new buildings. Consequently, more judgment is needed for design of the upgrading, including the choice of techniques, than in the design of new buildings. In addition, seismic upgrading is a relatively new activity and innovative techniques are in various stages of development. This document, therefore, places more emphasis on principles, experience, and access to information than on specific requirements and criteria.
Chapter 2

Seismic Deficiencies of the Building Structure

The choice of techniques for seismic upgrading of a building structure depends on its seismic deficiencies. Appendix C of the Guidelines for Seismic Evaluation provides a master list of 123 potential deficiencies. For this document it is useful to combine these deficiencies into the following more general categories:

- Lack of integrity/redundancy
- Inadequate strength/ductility
- Inadequate stiffness/adjacent buildings
- Irregularities/load transfer.

These categories are broken down into more specific deficiencies in Tables A1 to A6 in Appendix A. As a background to the principles of seismic upgrading (Chapter 3), the categories are discussed in more detail in this chapter.

2.1 Lack of Integrity/Redundancy

If the structure is not integrally connected, it will start to come apart during a strong earthquake. Experience shows that the most serious deficiency leading to progressive collapse of a building is lack of adequate anchorage of masonry or precast elements (walls, columns, beams, slabs) to the diaphragms and to each other. Other deficiencies in integrity relate to continuity of diaphragms (such as wood or precast concrete), especially around openings, and tying together of shear walls (tie-downs and connections between infill and frames).

Redundancy is another property of a building structure which, as shown by earthquake experience, helps prevent failures. Redundancy concerns not only the redundancy of the structure in resisting lateral loads (multiple shear walls and frames) but also its ability to resist vertical loads after local failure of a component such as a shear wall. Redundancy, however, is not always an advantage, especially when the “redundant” elements are of a brittle character, as discussed later.

2.2 Inadequate Strength/Ductility

The safety of a building, as well as the control of damage to the structure, depends very much on the behaviour of the building structure when subjected to large earthquake forces. The safety depends not only on the strength of the building structure but on its behaviour under cyclic overloading - its ductility, its energy-absorption capacity and its stiffness. In the case of moment frames, the safety of the building also depends on the ability of the frames to support the vertical loads in displaced configuration (the P-△ effect). Most evaluation statements in the Guidelines for Seismic Evaluation concern such properties.

Ductility under cyclic loading is therefore an important consideration, but it is often difficult to achieve through upgrading of existing structures. It can be achieved, however, by altering the structure by various techniques, as described in Chapter 3.

2.3 Inadequate Stiffness/Adjacent Buildings

Earthquake experience has shown that the lateral stiffness of the vertical structure is a major factor in the prevention of life-threatening failures and in the control of building damage. Lateral stiffness therefore becomes an important factor to be considered in the choice of upgrading for buildings in medium to high seismic zones. It is less important in low seismic zones because seismic ground displacements are relatively small.

Adequate in-plane stiffness of horizontal diaphragms (wood, metal deck) is also an important consideration in preventing instability failure of masonry walls in high seismic zones. This is covered in Appendix A of the Guidelines for Seismic Evaluation.
Compatibility in lateral stiffness of the vertical elements of the building, including architectural components, is another important consideration. The stiff elements attract the load and therefore fail first, whereas the flexible elements do not carry much load until after the stiff elements have failed. If, as a consequence of this, part of the building loses its vertical support, a dangerous progressive collapse can occur.

Related to lateral stiffness of the vertical structure is pounding from adjacent buildings or from adjacent parts of the same building separated by movement joints. Tall moment-frame buildings are flexible and can impact adjacent low stiff buildings. Damage can be very severe, particularly if storey levels do not line up. Impacts can also occur within a building if heavy components are not laterally supported by the structure.

2.4 Irregularities/Load Transfer

Dissymmetry in the layout of the lateral load-resisting structure or in the mass distribution can cause major torsional movements in an earthquake. Sudden changes in stiffness or discontinuities in both vertical and horizontal elements attract large local forces or deformations, leading to local rupture. Types of irregularities that attract large localized forces include:

- open fronts (shops, garages, etc.) in exterior walls at ground floor level
- columns supporting shear walls
- short concrete columns in moment frames (e.g., due to partial infills)
- shear walls or bracing offset from floor to floor.

Open fronts of buildings are a soft storey condition which has resulted in many collapses in recent earthquakes. Columns supporting shear walls are subjected to very large overturning forces, and short concrete columns attract large lateral forces and fail in a brittle shear mode. Offset shear walls or bracing result in large localized diaphragm forces.
Chapter 3

Principles of Seismic Upgrading

3.1 Objectives of Upgrading

Once rehabilitation of a building is deemed necessary for safety or other reasons (e.g., post-disaster function), there are a number of objectives, including life safety, that must be considered in the choice and design of the seismic upgrading. These may be listed as follows:

(1) life safety
(2) prevention of damage to building components and contents (damage control)
(3) minimum disruption of building use during upgrading
(4) proper functioning of the building after upgrading
(5) acceptable building appearance and heritage value
(6) minimum cost.

Objectives (3) to (6) are usually interrelated in the sense that they seek minimum structural intervention, provided the objectives of life safety and damage control are met. Minimum intervention will vary substantially from building to building and its achievement is very much a practice-oriented exercise involving considerable interaction of the engineer with the architect, owner and contractors. This chapter first summarizes available upgrading techniques and then discusses the principles the engineer will have to consider in the choice and design of the upgrading.

3.2 Conventional Upgrading Techniques

Conventional upgrading techniques do not require special devices or new materials. The following basic techniques are currently used for seismic upgrading:

New Shear Walls. This includes reinforced concrete, reinforced masonry, plywood-sheathed wood-stud walls and steel-plate shear walls. New shear walls should preferably be located between existing columns and connected to them, not only because this arrangement is structurally more effective but also because it may avoid the necessity of new foundations. New shear walls can be used to reduce torsional or other forces due to irregularities, as well as to increase strength and stiffness of the existing structure.

New Bracing. This can be executed in steel, wood, or occasionally in reinforced concrete. New bracing is usually in the vertical plane but can also be in the horizontal plane. The bracing should preferably be located within existing frames for the same reasons that shear walls should be located between columns. As is the case for shear walls, new bracing can be used to reduce torsional or other forces due to irregularities of the structure, as well as to increase the strength and stiffness of the vertical structure or diaphragms. A new technique is to incorporate special damping devices in new bracing; this is discussed in 5.1.

Infills. The systems described above for new shear walls can also be used to fill openings that are no longer needed in existing walls or diaphragms. Infills enhance stiffness as well as strength of existing walls or diaphragms. However, adequate strength of surrounding frame members must be assured.
**Overlays.** This includes cast-in-place concrete (shotcrete, toppings, etc.) and plywood. Mesh-reinforced cements or plaster and fibre-reinforced plastics (see 5.3) may also be used for safeguarding brittle components such as hollow clay tile or concrete columns. Overlays increase strength and stiffness of shear walls and diaphragms, and can be used as a means of tying different elements together for better integrity of the structure.

**Strengthening Members.** This includes adding components to strengthen or stiffen existing members, or to make them more ductile. A variety of methods exist, including reinforcing existing masonry (hollow block or coring of brick masonry), encasing with reinforced concrete, steel plates or fibre-reinforced plastics, and lateral bracing to reduce buckling length. Sometimes it is more economical and faster to replace existing members with new ones, as in the case of bracing systems. Sometimes it is better to strengthen existing components, such as unreinforced load-bearing masonry. Besides increasing strength, member strengthening can be used to make the structure more ductile by altering the mechanism of failure, for example by making reinforced-concrete columns stronger than the beams.

**Strengthening Joints.** This includes converting shear connections into moment connections in steel frames, strengthening bracing connections so that yielding takes place in the bracing members rather than brittle failure in the joints, nailing of wood sheathing, or welding of metal deck for strengthening diaphragms. Strengthening joints can be used to increase the strength of the structure and to make the structure more ductile by altering the mechanism of failure.

**Anchorage/Ties.** This includes anchorage of walls to floor or roof diaphragms for lateral support of the walls and for transfer of shear from the diaphragms to the vertical structure. It also includes anchorage of the vertical structure into the foundations. Anchorage devices provide integrity to the structure and are generally the most effective technique in terms of cost-versus-life-safety benefit.

Anchorage devices will also be useful when tying adjacent buildings or building portions together, in order to make them act as a unit and to avoid collision and hammering. Vertical tie-downs through floors, splices between diaphragm elements (e.g., at opening corners or between beams at supports) also provide integrity to the structure.

Precast assembly-type structures have not performed well in recent earthquakes as a result of connection failures and relative movements at the joints between the precast elements. One remedy is to strengthen and stiffen the ties.

**Chords/Collectors.** A chord is a continuous member placed along the outside edge of the diaphragm. It acts as a flange to resist diaphragm moment. A collector is a member incorporated in the diaphragm which 'collects' diaphragm shear and transfers it to the vertical structure. Chords and collectors tie diaphragms together and transfer diaphragm forces into the vertical structure. Sometimes reinforced-concrete toppings, plywood sheathing or steel trusses can accomplish the same objective. Collectors are sometimes called 'drag-struts.'

**Foundations.** Upgrading of foundations is generally expensive and should be avoided if possible except where, as shown by earthquake experience, foundation failure results in severe consequences as, for example, due to liquefaction, slides or pile failures. See *Guidelines for Seismic Evaluation* for the evaluation of foundations. There are a number of techniques for stabilizing liquefiable soils, sensitive clays, weak soils, or foundations on slopes.

New or enlarged foundations may be required for new gravity loads or for large overturning forces created by new shear walls or bracing. Conventional upgrading techniques include the addition of piles and the widening of existing footings, but generally it is easier to build new foundations away from existing ones. Soil and rock anchors are very cost effective in controlling uplift, both for upgrading of existing footings and for installing new ones.
3.3 Special Upgrading Techniques

A number of recently developed techniques are available which use special devices or new materials, and more are expected to be developed in the future. Those discussed in Chapter 5 of this Guideline include the following:

**Supplementary Damping.** In this technique, dynamic displacements and forces in the building are reduced by the action of energy-dissipating devices located at places of relative motion between storeys of the building. The devices convert kinetic energy into heat through sliding, yielding or viscous flow mechanisms. The technique is most suitable for flexible structures such as moment frames and is used in association with bracing or stiff/strong cladding.

**Base Isolation.** In this technique, much of the earthquake ground motion is prevented from being transmitted to the building by means of isolation devices located at the base of the building; these are very flexible in shear, or they slide. The result is a considerable reduction in building accelerations and forces, particularly for stiff buildings on firm ground.

**FRP/FRC Overlays or Encasing.** This includes composite overlays of fibre mesh and cement plaster or epoxy. It is applied to existing masonry for improved shear resistance and lateral strength and to concrete columns for better confinement and ductility.

3.4 Considerations in the Choice of Upgrading Techniques

The six objectives listed in Section 3.1 provide the basis for the choice of upgrading techniques to achieve minimum intervention. The following is intended to help the engineer in this task by a discussion of structural considerations related to seismicity and structural behaviour, and other considerations related to the upgrading construction process, the effect of upgrading on the function and appearance of the building, and cost.

3.4.1 Structural Considerations

**Seismicity.** The seismic ground motion corresponding to a design earthquake depends not only on the seismic zone but also on local ground conditions. Soft soils filter out high-frequency rock motions but amplify considerably the motions associated with low frequencies, and these can develop a resonance condition in the building structure, depending on its natural frequency. In the following, the seismicity in terms of the velocity-related seismic zone, \( Z_v \), should, for buildings on soft soil, be considered a level greater than the National Building Code (NBC) value.

For low seismic zones (\( Z_v \) of 2 or less) the main concern is the integrity of the structure, specifically anchorage of masonry walls to the diaphragms and lateral support of parapets, precast panels and masonry partitions. This means that the provision of anchorage and lateral support are likely to be the principal upgrading techniques used.

For medium to high seismicity (\( Z_v > 2 \)), a broader range of potential deficiencies of the structure must be addressed. Not only integrity, but lack of strength/ductility, lack of stiffness and irregularities of the structure become important. Often these deficiencies occur simultaneously. For example, high torsion, inadequate strength and excessive drift are frequently correlated as a result of irregularities in the building structure, as discussed later. For this reason it is desirable to use an upgrading technique such as well-placed new shear walls or bracing that simultaneously resolve these three major deficiencies. New shear walls or bracing may, however, require new foundations, as discussed later.
Irregularities. The most serious irregularities are soft or weak storeys and dissymmetry resulting in high torsion. Short columns in concrete frames and discontinuities in the vertical structure, such as offset shear walls, are also critical. For these types of deficiencies the most effective technique is to reduce irregularities by improving the load path. This is achieved by adding new components in the weak or soft locations (see Figure 3-1 for torsion), or by removing stiff non-structural components that cause high forces in brittle components, such as short concrete columns. The most effective technique such as new shear walls or bracing may, however, not be acceptable for other reasons (layout, building function, aesthetics or heritage aspects, etc.).

Irregularities such as setbacks in the vertical structure, re-entrant corners or split-level offsets in diaphragms are generally resolved by strengthening techniques (connections, splices, overlays, etc.) at these critical locations. Diaphragms may require local strengthening for large shear forces generated by shear walls that are offset from storey to storey.

Obviously, the building will have to be reanalyzed if there are significant changes to the vertical structure. If there still remain significant offsets of centres of stiffness and centroids of mass between floors, then a dynamic analysis should be carried out to determine member forces as required by the NBC. Dynamic analyses of structures composed of timber framing, masonry or precast concrete may be unreliable, however, unless calibrated to measured dynamic properties of the building structure.

Compatibility. This term refers to the ability of parallel elements of the vertical structure to work together to provide a system that behaves well in an earthquake. A very ductile but flexible moment frame is not compatible with a stiff brittle shear wall. The provision of such a frame as a second line of defence will not prevent collapse in situations where shear walls that are required to carry gravity loads suddenly collapse in an earthquake.

A satisfactory solution is to produce a system that is protected from deformations affecting the integrity of the walls, i.e. through elements that are of sufficient stiffness as well as strength. This can be done in different ways: by making the walls adequately strong to resist the forces they will attract; by improving their deformability; or by adding independent but sufficiently stiff elements.
The consequences of adding new structural components to the existing structure are large local forces transmitted into existing materials. Careful attention should therefore be given to the transfer of forces into the existing components by suitable connection details.

Compatibility considerations also apply to overlays where there may be differential movements due to shrinkage, temperature and possibly creep.

**Foundations.** Foundation upgrading is usually expensive and, depending on the occupancy and use of the building, can be disruptive. Often it is possible to upgrade the building structure without upgrading the foundations, particularly in regions of low to medium seismicity.

One of the major disadvantages of new shear walls or bracing is that they may require new foundations. One way of avoiding or minimizing foundation upgrading for new shear walls or bracing is to incorporate the new walls or bracing within existing structural frames. Another is to install supplementary damping devices in the structure to reduce earthquake forces into the foundations.

Uplift of the foundations is often considered a deficiency which should be corrected, but in many cases this may not be necessary. The Guidelines for Seismic Evaluation do not include anchorage to the foundations as a deficiency in low seismic zones. Whether or not uplift of the foundations is a serious deficiency depends on the amount of uplift and the damage that might occur as a consequence of this movement. In fact, foundation uplift may in some cases be considered as a positive feature, as discussed below under “System Behaviour.”

Another way to avoid foundation upgrading is to use a longer length of shear wall or more bracing, especially in the lower floors. For example, long lengths of an existing wood wall could be used as a shear wall with only minor nailing and anchoring; such surfaces usually require a general architectural upgrade anyway.

**System Behaviour.** As in the seismic design of new structures, in the design of upgrading it is desirable to achieve a system behaviour with the following properties under seismic actions: composite action and fuse behaviour.

The goal of composite action is achieved by adding new components in such a way as to make the existing and new components act together compositely and to correct the deficiencies of the existing structure. For example, lack of integrity is corrected by providing new or improved connections. The provision of new components which stiffen the existing structure, for example, helps prevent damage to brittle components such as unreinforced masonry.

The goal of fuse behaviour is achieved by making the structure perform in such a way that it ‘yields’ rather than ‘fractures,’ thereby preventing a progressive collapse. In assessing the effectiveness of fuse behaviour, it is useful to follow the behaviour of the upgraded structure under increasing lateral load, and to establish a sequence of the failure modes in various components (yielding, buckling, rupture, uplift, etc.).

Base isolation and supplementary damping make use of the fuse concept, as does a ductile stable yielding failure mechanism in the beams of frames, in contrast to a brittle unstable failure mechanism in the columns. For the same reason, a rocking mechanism in masonry walls is preferred to a brittle shear failure. Similarly it is preferable to allow uplift at the base of concrete shear walls rather than permit sudden failure in shear or compression, particularly if the shear walls are brittle as is often the case in old buildings.

The degree to which the fuse concept can be relied on, however, depends on the resulting displacements and the consequential damage. Displacements can be estimated on the basis of NBC elastic seismic forces (not reduced by the R factor) combined with realistic stiffness values for the resisting elements of the structure.
Damage Control. Control of damage to non-structural building components and to building contents may be required for life-safety (falling components, blockage of exits), to protect investment, or to maintain building function following an earthquake. Damage control is therefore often a major consideration in the choice of upgrading techniques.

Anchorage of building components to the main structure is one technique for damage control. This Guideline restricts itself to anchorage and support of walls (non-structural as well as structural) and parapets.

Control of displacements of the structure (e.g., storey drift) to values which can be tolerated by non-structural components is another technique, as is reduction of seismic building accelerations (which might damage special machinery or artifacts) by special upgrading techniques such as base isolation or supplementary damping.

3.4.2 Other Considerations

Apart from concerns about structural safety and serviceability, there are other considerations that have a major impact on the choice of techniques and the design of details.

Accessibility. This refers to the ability to gain access for the upgrading work, including the repair or replacement of building components and materials, the need for scaffolding, cranes, etc., and the ability to carry out the work in the available space. Difficult access is a major factor affecting upgrading techniques and cost. Foundations are the least accessible components of the structure and, as a consequence, usually the most costly to upgrade; techniques should therefore be sought to avoid foundation work.

Disruption. Disruption of the use and occupancy of the building during the upgrading can be another major consideration if the building remains in operation during the upgrading. For this reason seismic upgrading of the building structure is best carried out during a major renovation of the building, preferably when the building is unoccupied. In some cases this option is not available, and the upgrading must be carried out in stages, shifting people and operations around, undertaking work outside business hours, etc. In such cases, the duration of the disruption and its extent throughout the building becomes a major consideration in the choice of upgrading techniques and the design of details.

A special danger during upgrading is fire caused by welding sparks; precautions should be taken to prevent the occurrence of such fires.

Building Function. New structural components, such as shear walls or bracing, can negatively affect layout (traffic flow), daylight or other features of the building which relate to its use. For this reason, moment frames may be preferable to shear walls in certain locations. Thick overlays such as concrete toppings increase floor elevation, requiring adjustments to stairs, doors, elevators, etc.

Aesthetics. Some upgrading techniques are aesthetically unacceptable (see, for example, Figure 4-5). Cross-bracing can often have similar effects, and therefore moment frames are preferred in some locations, such as the front of a store. However, attention must be paid to stiffness considerations to avoid a soft-storey situation, resulting in large torsional displacements.
Heritage Values. Seismic upgrading of historic or unique buildings can be especially challenging. Heritage values are best served by the principle of minimum structural intervention, where the existing building components/materials having heritage value are not substantially altered, or are altered in a way that respects and maintains the heritage value of the existing building. This often requires considerable attention to the design of details. Obviously the intervention must also comply with the objectives described in 3.1 of life safety, damage control, and cost.

Such heritage concerns should therefore be addressed early in the choice of upgrading techniques and in the design of details in close cooperation with the architect, owner and conservation professional or organizations such as the Heritage Conservation Program of Public Works and Government Services Canada.

Cost. The cost of seismic upgrading of an existing structure can be substantially higher than the cost for seismic resistance in a new structure. Cost can sometimes be reduced by using one technique to eliminate a number of deficiencies, or by choosing new structural components that make the new and existing components act compositely. Techniques that eliminate the need for foundation upgrading or extensive structural upgrading can also be cost effective.

3.5 Design Criteria, Testing of Special Devices

This Guideline does not contain specific requirements for upgrading, including structural design criteria, or requirements for the testing and maintenance of special devices. A major project in the U.S. (referred to as the ATC-33 project) is currently underway to develop specific requirements and criteria by 1997, and these may subsequently be adapted for Canadian practice. In the meantime the criteria spelled out in the Guidelines for Seismic Evaluation could be applied to establish the adequacy of the seismic upgrading. However, the reduction factor of 0.6 for evaluation contained in the Guidelines for Seismic Evaluation should be increased to 1.0 for design of the upgrading, except in cases where it can be justified in terms of the objectives of this Guideline (risk to life, cost, damage control, heritage). Generally a more effective approach than reduced load factors is to carry out a staged upgrading based on risk mitigation and cost. More specifically, the following documents should be consulted for design criteria and testing of special devices:

(1) For upgrading existing unreinforced masonry bearing wall buildings, Appendix A of the Guidelines for Seismic Evaluation.

(2) For supplementary damping and base isolation, the NEHRP Recommended Provisions for Development of Seismic Regulations for New Buildings in conjunction with the current National Building Code and the relevant CSA standards (see also Sections 5.1 and 5.2).

For foundations, the strength properties of most soils may be increased for short term seismic forces, as recommended in the Guidelines for Seismic Evaluation.
Chapter 4

Upgrading Techniques – Conventional

Conventional seismic upgrading techniques include standard strengthening methods - placing connectors (anchors, nails, welds, bolts, dowels, splices, etc.) between existing structural components; connecting new components (members, overlays, infills) to existing components; building new sub-systems such as shear walls, bracing systems or piles and connecting them to the existing structure.

Another conventional technique, not discussed in this chapter, is to remove one or more upper storeys of the building in order to reduce the seismic forces to a safe level. These strengthening methods make use of standard construction procedures. Techniques requiring specialized devices or materials, such as supplementary damping, base isolators and fibre-reinforced plastic or cement overlays are considered in Chapter 5. Techniques for upgrading foundations are discussed in Chapter 6.

This chapter provides brief descriptions of techniques that can be used for upgrading the building structure, including a discussion of their relative merits based on the objectives and principles described in Chapter 3.

The details shown in Figures 4-1 to 4-16 are generic and are intended to illustrate concepts. Each detail must be designed to be workable under the conditions that actually exist.

Care must be taken in the detailing to ensure that load paths are achieved. In general, the use of large gusset plates, long fillet welds or stitching with many anchors is recommended to avoid concentrated forces at the interface of old and new components.

A global structural outlook must be maintained when developing an upgrade solution since an inappropriate solution may change the seismic characteristics of the building. For example, infilling a metal deck with concrete to increase its capacity will also increase gravity loads and possibly increase forces in some vertical elements because the diaphragm is much more rigid.

4.1 New Shear Walls, Bracing or Moment Frames

New shear walls may consist of reinforced concrete, reinforced masonry, plywood on studs, or steel. New bracing is generally steel but could be timber, and new moment frames are generally made of steel or reinforced concrete. These systems can be placed within the building, as interior or exterior walls or bracing (Figure 4-1a, b), or outside the building as buttresses (Figure 4-1c). Exterior buttresses may have an advantage in that work can be carried out primarily from the outside, minimizing disruption and damage to interior finishes, equipment, etc.

Preferably, new shear walls or bracing should be continuous to the foundations. If not, the diaphragms may have to be upgraded where vertical shear walls or bracing are offset between floors.

Choice of System: It is generally best to choose a new system that is compatible with the existing structural system. Compatibility in this Guideline usually refers to compatibility in the load-displacement response to a horizontal force. A new ductile moment frame, for example, is not compatible with an existing brittle shear wall. If the new system is in the same line of resistance as an existing system, or between two similar existing systems joined by a rigid diaphragm, then the new and old systems are essentially parallel and should, preferably, be compatible. There is less need for compatibility if the stiff system is ductile or if the incompatible systems are not acting in parallel.
GUIDELINE FOR SEISMIC UPGRADING OF BUILDING STRUCTURES

a) New shear wall (reinforced concrete or masonry)

Grouted dowels

b) New bracing (HSS or double angles preferred)

tie to suit existing conditions

Concrete, masonry or steel buttress wall

soil or rock anchors if required

c) External buttresses

Figure 4-1. New Shear Walls or Vertical Bracing

New moment frames or eccentric bracing are more compatible with existing moment frames and, if drift is not a problem, may be more effective and less costly, especially if the structure is accessible from the inside. A problem to be considered with new steel moment frames in an existing facility is the difficulty of moving large beams within a confined space.

Location. Location of new shear walls or bracing is a key decision which depends on non-structural as well as structural considerations.

Structural considerations in the location of new shear walls or bracing include the symmetry of the structure (torsional effects), the need for foundation upgrading, the need for new collectors/connectors for transferring diaphragm shear into the new shear walls or bracing, and whether the horizontal diaphragm is flexible or rigid. Sometimes the latter is difficult to establish, in which case both assumptions should be considered.

Earthquake forces due to irregularities such as torsion, or offsets in the vertical structure, can be substantially reduced by appropriate location of the new elements. Earthquake shear forces in the diaphragms can be reduced by adding new lines of lateral support as shown in Figure 4-1d.

Because foundation upgrading is usually expensive, it is desirable to try to make use of existing foundations by locating new shear walls or bracing within existing frames or to use light bracing instead of heavy shear walls. To reduce uplift and avoid upgrading of foundations, it is sometimes advantageous to lengthen bracing or shear walls so as to avoid large overturning moments in one place. If foundation upgrading is required, it may be better, however, to locate new shear walls or bracing away from existing foundations (inside or outside the building) because it is often easier to build new foundations than to upgrade existing ones.
Non-structural considerations affecting location include disruption if the building is to remain operational during upgrading, and the effects of the new shear walls or bracing on building function (layout, daylighting), building appearance and heritage value. For special service buildings such as hospitals, disruption can be a major problem and must be kept to an absolute minimum, for example by locating new shear walls or bracing outside the building. Occasionally these can conveniently be located within new additions to the building. Heritage considerations, on the other hand, tend to require that new shear walls or bracing be placed unobtrusively inside the building. New shear walls or bracing can also create obstructions to the functional use of the building and can affect the appearance of the building and its interior daylighting. However, concrete shear walls or buttresses can include fairly large openings provided they are properly designed. The location of new shear walls and bracing, therefore, must be worked out in close cooperation with the architect and the owner of the building.

Steel frames can be used as an exterior skeleton to transfer forces from the horizontal diaphragms to the foundations. When such frames are used, consideration must be given to maintenance; appropriate shapes should be used such as tubes or HSS sections with details that drain properly. Building security should also be considered as some arrangements of members may be easily climbable.

In summary, new shear walls or bracing should be considered especially where the existing building has the following deficiencies:
- Soft storeys
- High torsion
- High storey drifts
- Pounding
- Masonry or other components sensitive to storey drift.

### 4.2 Upgrading Existing Moment Frames

In medium to high seismic zones it is often more effective to incorporate new shear walls or bracing into existing frames than to upgrade existing moment frames. On the other hand, upgrading existing moment frames may be effective for low-rise buildings, especially if it avoids foundation upgrading and if the structure is easily accessible.

Conventional techniques for upgrading existing moment frames include the following:

**Steel Moment Frames:**
- Cover plates, clips and stiffeners (Figure 4-2)
- Gusset plates, knee braces
- Reinforced concrete encasement (Figure 4-3a)
- Steel jacketing (Figure 4-3b)
- Lateral bracing of unsupported flanges

**Concrete Moment Frames:**
- Steel jacketing (Figure 4-3b)
- Reinforced concrete encasement, (Figure 4-3a) or FRP encasement (Chapter 5)
- Repair of precast connections.

Steel moment frames are generally the easiest to upgrade, but if welding is used, it must be ensured that the existing steel is weldable. Recent earthquake experience with brittle failures at weld locations indicates that bolted connections may be preferable to welded connections. Reinforced and precast concrete frames are more difficult to upgrade, mainly because it is difficult to overcome deficient reinforcing or connection details.

Moment frames with existing infills of masonry require special attention. Because of the rigid infill, these systems act as shear walls and attract large forces. Failure can occur due to:
- lateral instability of the infill,
- crushing or splitting of the infill due to large in-plane forces,
- shear or tension failure of frame columns.
Figure 4-2. New or Improved Moment Connections

(a) Concrete encasement of columns

(b) Steel jacketing

Figure 4-3. Encasing or Jacketing Existing Members
Three upgrading strategies for infilled frames are:
(1) make the infill and frame act effectively as a shear wall (see Section 4.4),
(2) isolate the infill frame by means of gaps and resilient materials, while ensuring lateral stability of the infill,
(3) introduce new shear walls or bracing to stiffen the structure against infill damage while ensuring lateral stability of the infill.

The first strategy is effective if the infilled walls have sufficient capacity, the second if the frames have sufficient capacity and drift is not a problem, and the third will remedy both deficiencies. Lateral stability of the infill is ensured by direct contact with the frame around its perimeter, by lateral supports at the top (see Figure 4-16b) or by wall mullions or basketing with plaster/wire mesh or FRC overlays (see Section 5.3). Alternatively the infills can be replaced by other materials.

If an exterior wythe of masonry is located outside the frame, it may be vulnerable to delamination at the collar joint. Many brick masonry walls constructed of several wythes have inadequate connection (e.g., no headers or collar joints) between the wythes. This must be considered when developing an upgrade procedure.

### 4.3 Upgrading Existing Braced Frames

Existing braced frames are usually made of steel, but wood braced frames also occur. The types of steel bracing are shown in Figure 4-4. Cross-braced frames are most typical of older buildings, and these vary from flexible rod bracing (tension only) to stiff bracing which is strong in both compression and tension. Stiff cross-bracing that is connected together where the bracing intersects generally exhibits ductile behaviour in earthquakes. Tension-only cross-bracing exhibits poor behaviour because of yield elongation combined with 'slapping' of loose rods. Other types of bracing shown in Figure 4-4 include K bracing, and chevron or V-bracing, which also perform poorly compared to stiff cross-bracing. This is because compression buckling of a brace results in large unbalanced forces normal to the column or beam at the brace intersection. A new type of eccentric bracing has been developed which exhibits very ductile seismic behaviour. This bracing is discussed in 5.1.

Deficiencies most frequently found in existing braced frames are strength/ductility of the connections or members of the bracing system (including columns and beams), unfavourable type or configuration of the bracing system, and excessive drift in high seismic zones.

![Figure 4-4. Bracing Types](image-url)
Two upgrading strategies are: upgrade the existing bracing system, or add new bracing or shear walls. Both should be evaluated in terms of the objectives and principles described in Chapter 3.

For buildings more than three storeys in height, in medium to high seismic zones, consideration should be given to replacement of a tension-only bracing system by other means.

Conventional techniques for upgrading existing braced frames include:
- Strengthen or replace connections
- Strengthen or replace members
- Replace with better type of bracing
- Improve anchorage to the foundation

The choice of technique will depend on accessibility and the bracing configuration: K-, V- or chevron bracing is sometimes difficult to strengthen and may have to be replaced by another type.

Wood bracing is sometimes difficult to upgrade and members that are severely checked have to be replaced. The ductility of wood bracing is governed by the connection details and often the greatest improvement is obtained by providing connections that result in ductile behaviour of the structure.

4.4 Upgrading Existing Shear Walls

Four main types of shear walls are common in existing buildings: reinforced concrete or masonry, precast concrete, unreinforced masonry, and wood sheathing on studs. Behaviour varies considerably with type. Wood sheathing, reinforced concrete and reinforced masonry are the best performers, precast concrete less so, unreinforced brick or block masonry are relatively poor performers, while unreinforced hollow clay tile is the worst performer because of its friability.

Because new shear walls often need new foundations, increasing the strength/ductility of existing shear walls is sometimes preferable. However, where large irregularities exist in the building resulting in poor load transfer that produces high torsion, new walls or bracing may be more effective.

Conventional techniques for upgrading existing shear walls include:

Reinforced Concrete or Masonry:
- Infill (Figure 4-5)
- Reinforced concrete overlays (Figure 4-6a)
- Steel plating or bracing overlay
- Coupling beams
- Post-tensioning

Infill (Reinforced concrete or masonry)

Close existing opening with reinforced concrete or reinforced masonry

Figure 4-5. Infills (Vertical)
Precast Concrete:
- Infills (Figure 4-5)
- Reinforced concrete overlays (Figure 4-6a)
- Connection strengthening
- Pilasters/beams
- Tie-downs

Unreinforced Masonry:
- Reinforced concrete overlays (Figure 4-6a)
- Vertical reinforcing (Figure 4-7)
- Pilasters/columns
- Wire mesh/cement plaster or FRC
- Replacement

Wood:
- Additional nailing
- Plywood/OSB overlays (Figure 4-6b)
- Metal tie-downs and anchors (Figure 4-8)

Figure 4-6. Overlays (Vertical)
(a) Block masonry

Bars inserted directly from top or through side cut

(b) Brick masonry centre coring

Cored and grouted with rebars

Figure 4-7. Reinforcing Existing Masonry
(a) Foundation anchorage – Wood construction

![Diagram showing foundation anchorage]

Clip may be required

Anchor bolt

(b) Vertical tie-downs – Wood construction

![Diagram showing vertical tie-downs]

Tension splice strap

Figure 4-8. Vertical Tie-Downs and Anchorage
Infills are often less costly, but they may be unacceptable for reasons of appearance. Overlays are less disruptive if applied from the outside, but heritage or appearance considerations usually require them to be applied from the inside or on interior shear walls. Concrete overlays increase shear capacity and provide lateral support to existing masonry, but may require foundation upgrading. Coupling beams between shear walls which behave in a ductile manner may sometimes be cost-effective because they not only reduce wall overturning forces but improve the overall ductility of the connected system. Consideration should be given to the effects of relative movements between new overlays/infills and existing shear walls, e.g., shrinkage cracks and bowing.

The continuity of the shear wall system should be ensured by providing a continuous load path in shear, tension and compression. Existing concrete walls deficient in zone reinforcement can be upgraded by adding concrete nibs or bolting on steel members. Foundation tie-downs for precast walls to convert them into vertical cantilevers or additional shear transfer connections may be used as alternatives to strengthening existing connections. Tie-down splices and shear transfer connections may be required in wood shear walls, particularly for shorter walls, whereas longer wood-stud shear walls may not require tie-downs.

Concrete block walls can be upgraded for both in-plane and out-of-plane forces by the installation of vertical reinforcement in the hollow cores (Figure 4-7a). The concrete in the roof bond beam is chipped out and a reinforcing bar is inserted and anchored to the foundation by a grout-filled hole. Alternatively, hollow cores may be opened by saw-cuts near the top of each storey for inserting reinforcing bars. The reinforced core is then filled with concrete. If intermediate bond beams exist, they are carefully chipped out locally. An advantage of this procedure is that work can be carried out from the exterior, though the exterior face exhibits some patching, it is usually covered with an air barrier, insulation and a new finish. A similar technique is used for brick masonry (minimum thickness 300 mm) by drilling vertical cores (100 mm diameter) down through the masonry and placing reinforcing steel and grout (polymer cement) in the cored holes (Figure 4-7b). The technique provides greater lateral stability and better rocking resistance of narrow walls. For both methods the reinforcing may be post-tensioned.

Alternatively, unreinforced masonry can be upgraded by fibre-reinforced plasters (see 5.3) and by reinforced concrete overlays, including the option of removing the outer wythe to reduce weight and space.
4.5 Upgrading Existing Diaphragms

Existing diaphragms are generally a problem only for medium to high seismicity locations; however, transfer of shear from the diaphragm into the vertical structure may be a problem in lower seismic zones. Earthquake experience shows that most diaphragm failures are connection failures rather than failure of the diaphragm itself.

Two main types of diaphragms are common: flexible diaphragms consisting of wood or metal decking, and rigid diaphragms such as concrete slabs, concrete-filled metal decks, or floor structures which are horizontally braced. Rigid diaphragms transfer inertial storey forces to the vertical structure according to the relative stiffness of the vertical components. Flexible diaphragms tend to behave as beams between lateral supports and transfer inertial storey forces to the lateral supports. In high seismic zones, flexible diaphragms may deform excessively, resulting in failure of masonry walls (see Appendix A of Guidelines for Seismic Evaluation1).

Diaphragms act as horizontal beams in both bending and shear. It is therefore important that the integrity of the diaphragm be achieved. Integrity is achieved by the use of continuous chords or ties near the perimeter, splices or reinforcing at re-entrant corners, and collectors to transfer shears from the diaphragm into the vertical structure.

Conventional techniques for upgrading existing diaphragms include:

**Timber Diaphragms:**
- Nailing, stapling of existing diaphragms
- Plywood overlay (Figure 4-9a)
- Cross-walls (see Appendix A of Guidelines for Seismic Evaluation1)
- Nailing, bolting for shear transfer (Figure 4-12)
- Splices/blocking for chords, collectors (Figures 4-12, 4-14)
- New chords, collectors

**Steel Deck Diaphragms:**
- Welding
- Reinforced concrete overlay (Figure 4-9b)
- Steel bracing (Figure 4-10)
- Shear studs, anchor bolts, dowels for shear transfer (Figure 4-11)
- Steel chords, framing (Figure 4-11)

**Steel-Braced Diaphragms:**
- Replacement, reinforcement or addition of members or connections
- Secondary bracing
- Steel deck and/or reinforced concrete overlay with shear studs (Figure 4-9b)

**Concrete Diaphragms:**
- Reinforced concrete overlay (Figure 4-9c)
- Opening infills
- Additional dowels for shear transfer (Figures 4-9c, 4-13)
- Collectors under the diaphragms
- New chords, framing (Figures 4-13, 4-14)

It is usually more economical to upgrade wood roof diaphragms from above rather than by installation of bracing or plywood from below. This is because work from below may interfere with mechanical, electrical, sprinkler and architectural systems. On the other hand, it is sometimes more economical to upgrade steel deck diaphragms from below by the addition of horizontal bracing.

Cost and disruption are determined to a large extent by accessibility (removal and replacement of non-structural components such as flooring and partitions) and the extent of floor area requiring alteration. Reinforced concrete toppings have the disadvantages of increased floor elevation (requiring changes to stairs, doors, etc.), increased dead load, and sometimes increased torsion associated with stiff diaphragms.

Substantial upgrading of the diaphragm can sometimes be avoided by introducing additional vertical shear walls or bracing (see 4.1).
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(a) Plywood on Sheathing

(b) Concrete on Metal Deck

Shear connectors (channels, angles etc. or screws installed from above or below)

(c) Concrete on Concrete

Figure 4-9. Overlays for Diaphragms

(a) New bracing for steel construction

(b) New bracing for joists on concrete or masonry walls

Figure 4-10. Bracing for Diaphragms
**Figure 4-11. Shear Transfer and Chords (Metal Deck Diaphragms)**

- New chord and anchor
- Anchored with screws
- Bent plate and anchor
- Ledger angle (collector)
- Steel strap anchored to deck/chord
- Welds to strap and deck, as required
- Steel angle anchored to ledger/wall, as required

**Figure 4-12. Shear Transfer and Chords (Wood Diaphragms)**

- Clip angles
- New blocking

**Figure 4-13. Shear Transfer and Chords (Concrete Diaphragms)**

- Masonry
- Precast slab
- Chord
- Increased for shear transfer
- Concrete
- Precast slat
- Chord
(a) Collector in wood diaphragm

(b) Reinforcing an opening

(c) Splicing a glulam beam

Figure 4-14. Collectors and Splices for Diaphragms
4.6 Techniques for Lateral Support of Walls and Parapets

Lack of wall anchorage and slender unsupported parapets are the most prevalent life-threatening structural deficiencies in existing buildings. Upgrading for these deficiencies is generally much less costly and less disruptive than for other deficiencies of the building structure.

Both load-bearing and non-load-bearing walls should be addressed. Unbraced masonry and wood-stud partitions are common along egress routes. These partitions may support ceilings and other non-structural elements.

Techniques for anchorage or lateral support of walls and parapets are relatively simple, but care must be taken to ensure that details are designed for load transfer and that the work is properly carried out. For example, connections that depend on tension perpendicular to the grain in wood components connecting the anchor to the diaphragm must be avoided. Another common problem arises when lateral supports of the top of a wall do not permit vertical deflection of the structure above, thereby creating a load-bearing wall.

Conventional techniques for lateral support of walls and parapets include:

**Exterior Masonry/Concrete Walls:**
- Anchor bolts (Figures 4-11, 4-13, 4-15)
- Grouted dowels (Figures 4-9c, 4-13)
- Overlays (Figure 4-6a) or back-up walls

![Figure 4-15. Lateral Support of Exterior Walls](image-url)
GUIDELINE FOR SEISMIC UPGRADING OF BUILDING STRUCTURES

Exterior Curtain Walls:
• Connectors which allow racking

Masonry Parapets and Other Appendages:
• Bracing and anchoring (Figure 4-16a)
• Reduction in parapet height

Veneers:
• Veneer anchors

Partitions:
• Lateral supports (Figure 4-16b)
• Overlays or back-up walls

To minimize disruption, anchorage of exterior walls should preferably be carried out from the outside. Work will have to be carried out from the inside where the exterior is inaccessible or where the appearance of the anchors is unacceptable.

In many cases it is necessary to upgrade not only the connections but also to consider deficiencies of the wall itself. For example, unreinforced masonry walls may require the additional support that is provided by vertical reinforcing (Figure 4-7), overlays (Figure 4-6a) or beam/column back-ups.

Smaller, more numerous anchors rather than large anchors spaced far apart are preferred to achieve a ductile type of failure.

Figure 4-16. Lateral Support of Parapets and Partitions
Chapter 5
Upgrading Techniques - Special

This chapter provides guidance on three innovative upgrading techniques: supplemental damping, base isolation, and FRP/FRC overlays. It also references procedures for evaluating buildings that incorporate special damping and isolation devices. These techniques and devices are relatively new and in various stages of development. Therefore the guidance is, to a large extent, qualitative and the collaboration of specialist consultants may be required.

References for more detailed information are given for each special technique.

5.1 Supplemental Damping

It is well known that inelastic structural behaviour dissipates seismic energy that is fed into the building structure. As a consequence, the design lateral forces for which the structure must be designed are reduced. The NBC accounts for this by the force modification factor $R$ which ranges from 1 to 4; the higher the factor the better the energy dissipation. In addition to energy dissipation due to inelastic structural behaviour, energy is also dissipated as a result of inelastic deformation of non-structural building components and by sliding friction between these components. Such energy dissipation is taken into account in the evaluation criteria for unreinforced masonry buildings (Appendix A of Guidelines for Seismic Evaluation) arising from inelastic action of the wood diaphragms and partitions.

Supplemental damping devices can be inserted in a building to reduce the dynamic response by removing much of the energy induced in the structure by an earthquake. When appropriately installed, these devices allow seismic design to be shifted from the conventional reliance on ductility of the main structural elements to energy dissipation in the added devices. The devices help protect the building from severe damage or collapse by limiting resonance build-up and consequently reducing inelastic deformation of the structure.
There are three main types of damping devices - friction, metallic-yielding, and viscous/viscoelastic. Types and applications are described in Passive Energy Dissipation and Proceedings of Seminar on Seismic Isolation. An indication of their energy-dissipative behaviour is shown by hysteresis test curves in Figure 5-1.

Eccentric bracing, covered in Appendix D of CSA Standard S16.1, acts as an energy dissipating element, except that the 'device' is part of the structure and therefore not supplemental or easily replaceable.

It is important that the damping devices be tested prior to installation for assurance of their behaviour. It should also be ensured that their behaviour is maintained during the life of the building.

**Design Principles and Analysis.**
A general idea of the effect of supplemental damping on structural response can be obtained by examining the earthquake response spectrum for normal damping (5 percent critical) and supplemental damping (25 percent critical approx.) such as shown for two typical cases in Figure 5-2. Figure 5-2 shows that if the structure is upgraded without changing its period, the reduction in response is the difference between the lower and the upper response spectrum values corresponding to the fundamental building frequency. The damping devices, however, stiffen the building, consequently there is a decrease in its period $T$ in addition to an increase in its damping. This results in two benefits, first a reduced dynamic amplification at the original building frequency due to the increased damping, second a reduced displacement due to a decrease in period. This may not result in a decrease in base shear, but this is not so serious because the added braced dampers carry part of the lateral load. Figure 5-2b shows that increasing lateral stiffness as well as damping is particularly beneficial for structures founded on soft soil.

For efficient operation the supplementary devices should be located in the regions of the building where significant inter-storey displacements occur. For stability of the structure, the lateral resistance of the structure should increase with increasing displacement. It is therefore important that, except for the devices, the structural system remain elastic, or nearly so, during the design earthquake. It may be necessary to use conventional techniques to strengthen some structural components, such as columns in lower storeys that attract extra axial loads from the new braced devices. Because of the added damping, however, these loads are likely to be smaller than those resulting from the presence of the new bracing alone.
5.2 Base Isolation

Base isolation uncouples a building from its foundation, allowing it to “float” on flexible elements. This limits the energy transferred into the building by an earthquake. Isolation protects a building in two ways. First, the isolators reduce the overall lateral stiffness of the building and, as a result, the fundamental period of the building is shifted outside the period region over which most of the energy of the earthquake is concentrated. Thus most of the seismic energy is not transmitted to the building. Second, the isolators dissipate energy which reduces resonance build-up that might occur at a natural frequency of the isolated building. The isolators, however, should be stiff enough to prevent unacceptable building sway under wind loads.

The fundamental period of a base-isolated building should be substantially greater than both its fixed-base equivalent and the predominant periods of the ground motion. Otherwise, the long period earthquake motions corresponding to the fundamental lateral period of the isolated building will be amplified. Base isolation is therefore generally unsuitable for buildings on very soft soils (e.g., Mexico City) or for tall buildings whose fundamental lateral frequency without base isolation approaches that for the building mass resting on the base isolators. To control such low-frequency motions, the base isolation system must dissipate energy, typically an equivalent damping ratio of 0.10 to 0.20.

The devices and their locations should be designed to achieve maximum effective energy dissipation in the structure, in order to minimize inter-storey displacements and avoid excessive forces, particularly those which would require new foundations, collectors, connections, etc. The design of upgrading involving supplemental damping devices therefore requires more effort than a design using conventional upgrading techniques. However, in some cases the benefit can be considerable in reduced cost and disruption.

Specific requirements for the design of building systems containing damping devices, and for their testing and maintenance, are currently being developed. Tentative requirements for their use in new buildings are contained in NHERP Recommended Provisions; many of these requirements also apply to the upgrading of existing buildings. The NHERP Recommended Provisions allow a static analysis for buildings under certain conditions, including buildings with devices that are viscous or viscoelastic. Otherwise a dynamic procedure involving either the response spectrum method or, more generally, a time-history nonlinear analysis is required. The latter method is specified in NHERP Recommended Provisions for friction or yield devices, or where structural response will be significantly nonlinear in a design earthquake.

A number of applications are described in Passive Energy Dissipation and Proceedings of Seminar on Seismic Isolation.
GUIDELINE FOR SEISMIC UPGRADING OF BUILDING STRUCTURES

Basic Model

Isolators: Low stiffness, high damping

Figure 5-3. Effect of Base Isolation (Reprinted by permission)

These considerations become evident by comparing the response spectra of Figure 5-3 for a stiff building (T = 0.5 s) versus a very flexible building (T = 2 s) and for firm ground versus soft soil.

During an earthquake, large lateral displacements will occur above the isolators at the base of the building. Therefore, moveable joints are required in the services to the building (pipes, sidewalks, etc.). There must also be a substantial separation of the building from adjacent properties. Because base isolation involves considerable upgrading of the building foundations, it is generally considered economically viable only for important special-purpose and heritage buildings in medium to high seismic zones.

One advantage of base isolation is that it results in a substantial reduction of building accelerations, such that the risk of damage to the building and its contents is small, increasing the likelihood of continued function of the building during and after an earthquake. Base isolation also protects contents such as instruments, computers and precious artifacts in museums. However, additional conventional upgrading of the building may be required in high seismic zones. Another possible advantage is that installation of the isolators at the foundations may be less disruptive to the use of the building than conventional upgrading techniques.
Currently there are three main types of base isolation devices: elastomeric, sliding and hybrid. The most popular ones in use consist of deep elastomeric pads laminated with steel plates, which incorporate high damping rubber or a lead core to provide energy dissipation. Sliding isolation devices have also been used in North America. Hybrid isolation systems combine sliding with elastomeric damping. More information on these devices is contained in *Proceedings of Seminar on Seismic Isolation.*

A base isolation system should provide increasing resistance with increasing displacement so that the building returns to its original position after the earthquake.

Requirements for the design of base isolated buildings and for the testing and maintenance of base isolators are contained in the *NHERP Recommended Provisions.* Although these requirements apply to new buildings, many of them would also be appropriate for existing buildings. The *NEHRP* publication contains three analysis procedures in order of increasing complexity and wider application - a static procedure, a spectrum procedure and a time-history dynamic procedure. The conditions for which the procedures may be used relate to soils, proximity of active faults, seismicity, building period, building irregularities and properties of the isolation system.

Further information, including a number of applications, are described in *An Introduction to Seismic Isolation,* *Proceedings of Seminar on Seismic Isolation,* *Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation,* and *Seismic Retrofit of Historical Buildings Conference Workshop.*

### 5.3 FRP/FRC Overlays and Encasements

Fibreglass has been used for many years to upgrade wood boats. Fibre-reinforced plastics (FRP) and fibre-reinforced cements (FRC) incorporating glass, carbon and other materials are now being used for seismic upgrading of buildings. Current applications include FRC overlays of masonry walls and partitions, and FRP encasement of concrete columns and architectural terra-cotta.

**Masonry Walls/Partitions.** Fibre-reinforced cement (FRC) strengthening of existing masonry is currently used for seismic upgrading in New Zealand and Australia. The FRC system is a plaster skin process (Figure 5-4) which can be used for improving both in-plane and out-of-plane strength of masonry walls. The FRC process consists of one or more layers, depending on the strength required, of a particular high tensile strength woven fibreglass mesh which is embedded in a fibre-reinforced plaster. The process can be applied to one or both sides of a wall. Zone steel with plaster thickening may be required at the ends of shear walls. The manufacturers have developed some specialized details for developing continuity and for connecting the walls to the floors and roofs.

![Fiberglass reinforced cement strengthening](image)

**Figure 5-4. FRC Strengthening of Masonry Walls**
**Encasement of Concrete Columns.**

FRP overlays of concrete columns is currently being used for seismic upgrading of columns in a number of bridges and buildings in the United States\(^{18,19}\). A fibre/epoxy jacket is wrapped around the column in large bands of woven unifabric and this cures in place (Figure 5-5). The jacket may be post-tensioned circumferentially by injecting grout under pressure into a bladder wrapping between the FRP jacket and the concrete column. The effect of the post-tensioning is to confine the concrete column so as to prevent failure of reinforcement at critical laps near the joints and to increase the shear resistance of the column such that it fails in a ductile flexural mode. The lateral stiffness of the column between floors is not increased substantially (such stiffness would attract more earthquake load to the column) because FRP wrapping is much stronger in the circumferential direction than in the longitudinal direction. In cases where the confinement stress is not needed, non-post-tensioned FRP encasement can be used to increase shear strength in order to ensure ductile flexural behaviour. For more information see *Fibre Wraps Migrate East.*\(^{19}\)

A similar technique involving the application of FRP overlays to existing masonry walls is also under investigation.

![Figure 5-5. FRP Encasement of Concrete Columns](image-url)
Chapter 6

Upgrading Techniques – Foundations

Historically, few foundations on level competent ground have failed during earthquakes. Foundation failures have occurred where the underlying soils have comprised loose saturated sandy or silty soil, or very soft sensitive clays, or where foundations have been located on steep slopes.

The advice of a competent geotechnical engineer and/or geologist should be sought whenever the building is located on soft or loose soil or where geological seismic site hazards exist.

Upgrading of foundations is generally expensive because of access difficulties. The need to upgrade the foundation to resist gravity and seismic forces, however, arises in circumstances that require one or more of the following five objectives to be met:

1. to provide new foundations for vertical elements added in the upgrading;
2. to enhance the bearing, uplift and lateral capacity of the existing foundation;
3. to strengthen the connections between the foundations and vertical elements;
4. to prevent potential loss of soil support (e.g., by soil stabilization), and
5. to implement base isolation.

Objectives (1) and (2) are generally achieved by the application of conventional techniques for upgrading described in 6.1 or by the application of soil stabilization techniques described in 6.2. Objective (3) is generally achieved by the application of techniques described in 4.2 to 4.4 and 6.1. Objective (4) is achieved by the application of soil stabilization techniques described in 6.2. Objective (5) is achieved by the application of conventional techniques described in 6.1 and the use of special devices described in 5.2.
GUIDELINE FOR SEISMIC UPGRADING OF BUILDING STRUCTURES

(a) Underpinning an existing footing

(b) Transmitting existing footing load to competent subsoil using soil anchors

(c) Addition of needle beam and drilled piers to an existing strip footing

Figure 6-1. Conventional Upgrading of Foundations

6.1 Conventional Techniques for Upgrading Foundations

Seismic upgrading of the superstructure may require upgrading of the foundation, particularly if there are new shear walls or bracing. The foundations need to accommodate increased gravity loads as well as seismic shear and overturning forces. An increased allowable bearing capacity is usually appropriate for short-term seismic forces.

Techniques: Existing continuous (strip) or spread footings may be subjected to excessive bearing pressure or even uplift. Techniques to alleviate these conditions include:

- underpinning the existing footing so that the upgraded footing is founded on competent subsoil (Figure 6-1a)
- adding soil anchors (Figure 6-1b), drilled piers, or piles (Figure 6-1c)
- increasing the number of vertical load-carrying elements in the superstructure.
Pile foundations may be subjected to excessive tensile and compressive loads from the combination of seismic and gravity loads. Their lateral capacity may also be inadequate for transferring the seismic shears from the pile caps and the piles to the subsoil. The pile foundation capacity can be increased by:

- driving additional piles and enlarging the existing pile cap
- introducing tie beams between pile caps to assist in redistributing the loading.

Mat foundations may occasionally have inadequate moment capacity to resist the combined gravity and overturning forces. This deficiency may be corrected by providing a locally thickened reinforced-concrete section such as inverted column capitals.

To prevent foundation damage due to seismic shear, the passive resistance of the founding soil can be mobilized by introducing perimeter and tie beams or shear keys which extend into the underlying soil. These can also be used for tying footings together and redistributing forces. Alternatively, anchors, drilled piers or raked piles can also be used.

For buildings constructed on steep hills, the columns and piers should be designed to resist earthquake loads, and foundations should rest on stable ground. Piles with adequate lateral capacity should be used for buildings over the water along bay shores and river banks.

**Relative Merits.** Conventional procedures such as those shown in Figure 6-1 may be effective for some applications. Because foundation upgrades tend to be costly and disruptive, other seismic upgrading schemes should be considered, such as soil stabilization or additional shear walls, bracing or buttresses. Underpinning existing footings is usually not appropriate for buildings founded on a thin clay crust overlying liquefiable soils (e.g., some buildings in Richmond, B.C. - see *Earthquake Design in the Fraser Delta*).
6.2 Soil Stabilization

Seismic soil failures causing building damage include: loss of soil strength due to build-up of dynamic pore pressure, liquefaction, lateral spreading of soil, excessive horizontal and vertical ground movements due to settlement of natural soil deposits or man-made fills, slope instability, or fault movements. Chapter 10 of the Guidelines for Seismic Evaluation and the Canadian Foundation Engineering Manual provide guidelines for evaluation of these issues. The maintenance of slope stability in diverse geological and topographic settings is mainly a geotechnical problem and is beyond the scope of this document. In general, a competent geotechnical engineer should be engaged to assist the owner or structural engineer to assess the geotechnical issues involved.

The following describes soil stabilization techniques and provides general guidance which may be used to prevent loss of soil support in an earthquake.

Soil stabilization techniques have been developed for many applications in geotechnical engineering, including ground improvement, foundation rehabilitation, groundwater control, excavation support and pollution control. Comprehensive state-of-the-art reports and practical applications of soil stabilization techniques are contained in Soil Improvement: History, Capabilities and Outlook, Soil Improvement: State-of-the-art, Improvement of Liquifiable Foundation Conditions, Soil Improvement: Ten Year Update, and Grouting, Soil Improvement and Geosynthetics. The selection of the most appropriate and economical technique for a particular project depends on many factors, including site and ground conditions, subsoil grain size distribution, effects on surrounding environment, adjacent buildings, and cost. Different techniques are often combined on the same project to obtain the optimum remediation scheme. The effectiveness of the scheme can often be checked by in situ soil testing or full-scale load testing. These techniques are continually evolving as new technology becomes available and new applications are found.

Applicable grain-size ranges for soil stabilization techniques are shown in Figure 6-2. Superimposed in Figure 6-2 is a grain-size range for subsoils susceptible to liquefaction. The application of these techniques for existing structures and foundations, however, is often limited by the following constraints:

- limited access or headroom for construction equipment
- limits for vibration or physical impacts on existing structures
- disruption to the functional use of the building and the adjacent area
- field control and checking required to ensure the quality of soil improvement.

![Figure 6-2. Applicable Grain-Size Ranges for Soil Stabilization Techniques](image-url)
Table 6-1. Soil Stabilization Techniques for Existing Buildings

<table>
<thead>
<tr>
<th>Technique</th>
<th>Soil Improvement Function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Densification</td>
</tr>
<tr>
<td>Chemical grouting</td>
<td></td>
</tr>
<tr>
<td>Compaction grouting</td>
<td>Y</td>
</tr>
<tr>
<td>Minipiles</td>
<td></td>
</tr>
<tr>
<td>Vertical Drainage Wells</td>
<td></td>
</tr>
<tr>
<td>Jet Grouting</td>
<td></td>
</tr>
<tr>
<td>Soil Mixing</td>
<td></td>
</tr>
<tr>
<td>Vibro-Compaction</td>
<td>Y</td>
</tr>
<tr>
<td>Vibro-Replacement</td>
<td>Y</td>
</tr>
<tr>
<td>Compaction Piles</td>
<td>Y</td>
</tr>
</tbody>
</table>

Soil stabilization techniques used for seismic upgrading of existing foundation soils are listed in Table 6-1, together with their basic soil improvement functions. These functions include:
- densification of loose soils or strengthening of weak soils beneath existing structures and/or in adjacent areas on sloping ground,
- underpinning and strengthening the subsoil support of existing foundations,
- improvement of subsoil for the installation of new foundations, and
- drainage of subsoils to mitigate seismic pore pressure build-up.

Some techniques are more adaptable for use inside an existing building, such as chemical and compaction grouting, drainage wells and minipiling. Other techniques such as minipiling or jet grouting may involve drilling inclined holes from outside the building. Finally, there are techniques involving equipment that is mainly suitable for use in open space, such as soil mixing, vibro-compaction and vibro-replacement, and compaction piles. In adopting any of these techniques, careful selection of competent and experienced specialist contractors as well as a well-planned quality control program during construction are essential.
Chemical grouting (Figure 6-3a) involves injecting solutions of two or more chemicals into the soil pores to form solid precipitates or sandstone-like masses. The method relies on grout permeation and is effective in clean cohesionless soils. Compaction grouting (Figure 6-3b), on the other hand, injects low slump grout under high pressure to densify soils by displacement. The method can be used to reinforce the weak subsoil underneath existing footings in most subsoils. Foundation heaving, however, should be carefully controlled.

Minipiles, also known as pinnpiles or micropiles, are drilled and grouted piles with diameters less than about 300 mm (see Figure 6-3c). They can be installed with relatively small equipment in confined spaces not accessible to conventional piling equipment. They are used to transmit loads to competent materials and can be used to provide compression, tension or shear capacities. They can also be used to stabilize a slope.

Figure 6-3. Soil Stabilization, Minipiles
For relief or prevention of potential dynamic pore water pressures developed in the subsoils, *vertical gravel drains or drainage wells* can be installed around and/or inside structures. If properly installed, the gravel drains will prevent liquefaction by mitigating pore pressure build-up caused by earthquake shaking. Drainage wells can also be installed with permanent dewatering to lower the groundwater table below the subsoil zone susceptible to liquefaction.

*Jet grouting* (Figure 6-3d) uses high-velocity water jets to cut and lift the soil to the surface, creating a cavity into which cement slurry is injected. This technique can be used in practically all soils to form soil-cement columns or “soilcrete,” and is useful for underpinning or strengthening existing foundations. A technique similar to jet grouting is *soil mixing* (Figure 6-3e) for which a large-diameter auger or a series of augers penetrate and mix the soil in situ with a controlled amount of cement slurry to form soil-cement columns. The soil mixing technique, however, requires a relatively large crane or rig.

*Vibro-compaction or vibro-flotation* involves the insertion of a powerful vibrating probe into the ground to densify granular soils with less than about 20% silt and clay fines (see Figure 6-3f). Vibro-replacement uses a similar powerful depth vibrator to densify the soils, as well as to install compacted gravel or stone columns. This technique can be used in finer soils where the stone columns act to reinforce the soil mass. Compaction piles are used to densify granular subsoils by the displacement of the soils around the driven piles. Because of the size of crane or rig involved, these techniques are mainly used for improving the condition of a sloping ground around the existing buildings in order to minimize the impact of deformations of surrounding soil on the building.
References


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**Supplementary Reading**


Appendix A

Checklist of Seismic Upgrading Techniques

This Appendix provides a checklist of techniques currently used to upgrade buildings containing seismic deficiencies. The checklist is organized in tables, where each table lists techniques for deficiencies related to a subsystem of the existing building structure, i.e. moment frames, braced frames, shear walls, diaphragms, lateral support of walls and foundations.

The techniques are listed in terms of categories (infills, overlays, connections, new walls or bracing, collectors, etc.). Specific techniques (nailing, concrete overlay, plywood overlay, anchorage details, etc.) for each category are described in more detail in Chapters 4 to 6, along with their relative merits based on the principles described in Chapter 3. For easy access, Tables A1 to A6 list the appropriate pages and figures for each technique category in Chapters 4 to 6. More detailed checklists of conventional techniques for each category are contained in Chapters 4 and 6. To relate the deficiencies listed in Tables A1 to A6 to those found by application of the Guidelines for Seismic Evaluation, see Chapter 2.

Table A1. Moment Frames (Steel, Concrete)

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>Strengthen Connections or Anchors* p. 15-16 Figure 4-2</th>
<th>Strengthen Members* p. 15-16 Figure 4-3</th>
<th>New Walls, Infill or Bracing p. 13-15 Figure 4-1</th>
<th>Supplementary Damping or Base Isolation p. 29-33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Connection Strength</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Member Strength/Ductility</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Short Concrete Columns</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Failure of Infill</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Uplift</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* For specific techniques, see p. 15.

Table A2. Braced Frames (Steel, Concrete, Wood)

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>Strengthen Connections or Anchors* p. 17-18</th>
<th>Strengthen Members* p. 17-18</th>
<th>New Walls, or Bracing p. 13-15 Figure 4-1</th>
<th>Supplementary Damping or Base Isolation p. 29-33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Member Strength</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Connection Strength</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Uplift</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

* For specific techniques, see p. 18.
### Table A3. Shear Walls (Concrete, Masonry, Wood)

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>Upgrading Technique</th>
<th>Infills*</th>
<th>Overlays*</th>
<th>Reinforcing, Tie-Downs or Anchors*</th>
<th>New Walls or Bracing</th>
<th>Base Isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>p. 18-22</td>
<td>p. 18-22</td>
<td>p. 18-22</td>
<td>p. 13-15</td>
<td>p. 31-33</td>
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<tr>
<td></td>
<td></td>
<td>Figure 4-5</td>
<td>Figure 4-6</td>
<td>Figure 4-7, 4-8</td>
<td>Figure 4-1</td>
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</tr>
<tr>
<td>Torsion</td>
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<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Strength</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Lateral Support (see Table A5)</td>
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<td></td>
<td></td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coupling Beams</td>
<td>Y</td>
<td></td>
<td></td>
<td>Y</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Interpanel Connection (Precast)</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td></td>
<td></td>
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<tr>
<td>Cripple Foundation Walls</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
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<td></td>
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<tr>
<td>Uplift</td>
<td></td>
<td></td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

* For specific techniques, see p. 18-19.

### Table A4. Diaphragms (Concrete, Steel, Wood)

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>Upgrading Technique</th>
<th>Overlays**</th>
<th>Horizontal Bracing*</th>
<th>Collectors, Splices, Chords*</th>
<th>Strengthen Connections*</th>
<th>New Walls** or Vert. Bracing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Figure 4-9</td>
<td>Figure 4-10</td>
<td>Figure 4-11 to 4-14</td>
<td>Figure 4-11 to 4-14</td>
<td>Figure 4-1</td>
</tr>
<tr>
<td>Shear Strength</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Horizontal Drift</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear Transfer</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Integrity</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

* For specific techniques, see p. 23.
† Includes nailing or welding of existing decking to structure.
** Includes cross-partitions acting as dampers.
Table A5. Lateral Support of Walls (Masonry, Precast)

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>Anchors, Connections* (p. 27-28, Figure 4-15, 4-16)</th>
<th>Local Bracing* (p. 27-28, Figure 4-16)</th>
<th>Overlays* (p. 18-22, Figure 4-6)</th>
<th>Vertical Reinforcing (p. 19-22, Figure 4-7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient Anchorage</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Slenderness</td>
<td>Y</td>
<td></td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

* For more specific techniques, see p. 19, 27 and 28.

Table A6. Foundations (Concrete, Masonry, Wood)

<table>
<thead>
<tr>
<th>Deficiency</th>
<th>Upgrading Technique</th>
<th>New Footings (p. 36-37, Figure 6-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil Stabilization (p. 38-41, Figure 6-2, 6-3)</td>
<td></td>
</tr>
<tr>
<td>Bearing Capacity</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Settlement</td>
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<tr>
<td>Liquefaction</td>
<td>Y</td>
<td></td>
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<tr>
<td>Slides</td>
<td>Y</td>
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</table>