Damage from 20th century earthquakes in eastern Canada and seismic vulnerability of unreinforced masonry buildings

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This paper has been prepared as a reminder of past damaging earthquakes in eastern Canada and as a testimony of the damage suffered; isoseismal maps of five selected eastern Canadian earthquakes are presented as well as illustrations of their effects. Although features of the four older historical events reviewed herein are reasonably well documented (although not to present standards), data of engineering significance needed to perform accurate seismic-resistance evaluations have been for the most part lost owing to the time elapsed. Hence, the damage examples presented herein should not be construed as a comprehensive survey but rather as a sampling of noteworthy failures. Since most of the structural damage produced by these earthquakes was suffered by unreinforced masonry buildings, an overview of the seismic risks they constitute and their main modes of failure is presented. The first step of a coordinated seismic risk reduction plan is also formulated; its application is recommended for the mitigation of economic and human losses in future eastern Canadian earthquakes.

Key words: case histories, earthquakes, eastern Canada, seismic risk reduction plan, structural damage, unreinforced masonry buildings.

Cet article a pour objet de rappeler certains séismes destructeurs qui se sont produits dans l'est du Canada et de faire état des dommages occasionnés. Des cartes isoséistes de cinq tremblements de terre survenus dans l'est du Canada sont présentées ainsi que des illustrations de leurs effets. Bien que les caractéristiques des quatre plus vieux événements considérés dans cette étude soient relativement bien documentées (bien que non conformes aux normes actuelles), les données d'importance technique nécessaires à la réalisation d'évaluations parasismiques précises ne sont plus disponibles étant donné la période de temps écoulée. Par conséquent, les exemples de dommage présentés dans cet article ne devraient pas être considérés comme une revue exhaustive, mais plutôt comme un échantillonnage des défaillances dignes de mention. Puisque la plupart des dommages structuraux ont été causés à des bâtiments de maçonnerie non armée, un bref rappel des risques qu'ils présentent et de leurs principaux modes de défaillance est proposé. La première étape d'un plan coordonné de réduction des risques sismiques est également décrite; son application est recommandée pour limiter les pertes de vie et les pertes financières qui pourraient être occasionnées par de futurs séismes dans l'est du Canada.

Mots clés : étude de cas, tremblement de terre, est du Canada, plan de réduction des risques sismiques, dommage structural, édifices de maçonnerie non renforcée.

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1. Introduction

Eastern Canada is located within a stable region of the North American tectonic plate and as such, experiences a relatively low rate of earthquake activity. Nevertheless, large and damaging earthquakes have occurred here in the past and will inevitably recur in the future.

Although some recent earthquakes (such as the 1988 Saguenay and 1989 Loma Prieta earthquakes) have increased public awareness of the ever present potential for a major earthquake in the region, much remains to be done. The false perception that previous earthquakes have caused little damage, combined with the relatively long period between damaging events, has instilled a complacency towards seismic risk in the general public. Population has grown and the infrastructure has expanded considerably since the last damaging earthquake in many eastern Canadian seismically active regions, and consequently so has the potential for earthquake-induced losses.

This paper has been prepared as a reminder of past damaging earthquakes in eastern Canada and as a testimony of the damage suffered; isoseismal maps of five selected eastern Canadian earthquakes are presented as well as illustrations of their effects. Since most of the structural damage produced by these earthquakes was suffered by unreinforced masonry buildings, an overview of the seismic risk they constitute and their main modes of failure is presented. The first step of a coordinated seismic risk reduction plan is also formulated; its application is recommended for the mitigation of economic and human losses in future eastern Canadian earthquakes.

In this paper, references are provided to some seismological studies that describe these earthquakes in more details. Although features of the four older events reviewed herein are reasonably well documented (although not to present standards), data of engineering significance needed to perform accurate seismic-resistance evaluations have been for the most part lost owing to the time elapsed. Hence, the damage examples presented herein should not be construed as a comprehensive survey but rather as a sampling of noteworthy failures. Since one of our main goals was to gather earth-

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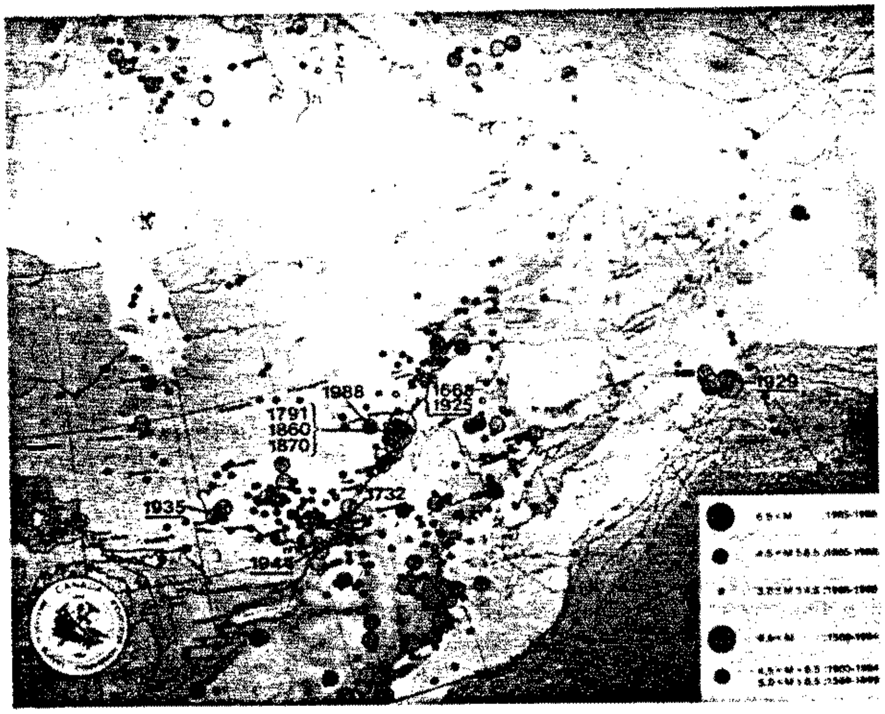

FIG. 1. Seismicity of eastern Canada and surrounding regions in the period 1568–1988 (adapted from Anglin et al. 1990).

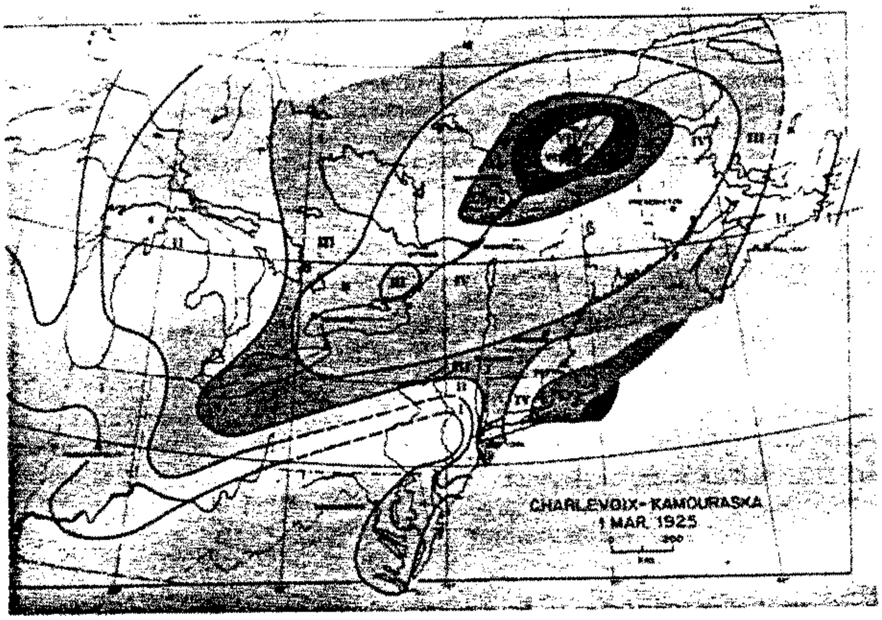

FIG. 2. Rossi–Forel isoseismal map of the M6.7 1925 Charlevoix–Kamouraska earthquake (from Smith 1966).

quake damage photographs, potential sources of photographic documentation (archives of the Geological Survey of Canada, newspapers, historical societies) were searched more thoroughly than were the written archives. Thus, readers should not assume that all cases of damage due to these earthquakes are described in this paper. In the following, some figures have a reference to the publication where they were first published; others were never published and are credited to their respective author. Finally, none of the earthquakes reviewed produced surface rupture; a detailed description of the seismo-tectonic structure of eastern Canada is available elsewhere (Basham 1987; Adams and Basham 1989).

2. Eastern Canadian seismicity

Historically, some moderate to strong earthquakes have been reported to occur in eastern Canada. For events that occurred before this century, written accounts of earthquakes and of the induced damage are the sole source of information. Although these reports generally lack the thoroughness of damage observations needed for reliable engineering assessments, seismologists were able, using the description of felt areas and effects, to estimate the approximate magnitude of the five damaging earthquakes that occurred prior to the 1900s. They are the following: 1663 (Charlevoix–Kamouraska; magnitude 7); 1732 (Montreal; magnitude 6);

1791 (Charlevoix; magnitude 5.5); and 1860 and 1870 (Charlevoix–Kamouraska; magnitude 6 and 6.5 respectively). Although the population distribution was much less than it is today, these earthquakes damaged some construction, mainly masonry chimneys which were the most vulnerable elements in early Canadian homes of wood construction or thick stone masonry.

In the 20th century, the installation of seismographs and subsequent improvement in the seismographic coverage of eastern Canada have allowed a closer monitoring of seismic activity. Currently (1993), more than 30 seismograph stations are located in eastern Canada in addition to 25 strong-motion recorders. The detection and location threshold is now better than magnitude 2.5 in most of the densely inhabited areas (Wetmiller et al. 1989). A few areas of enhanced activity, such as the Charlevoix–Kamouraska region, are monitored by denser local networks.

Figure 1 presents a selection of earthquakes from the Canadian earthquake epicentre file (Anglin et al. 1990). The map shows regions of enhanced earthquake activity and locations of some significant earthquakes. The epicentres of the five earthquakes described in this paper are indicated with years. They are the 1925 Charlevoix–Kamouraska earthquake (also called in older reports the St. Lawrence or La Malbaie earthquake); the 1929 Grand Banks (or Laurentian Slope) earthquake; the 1935 Timiskaming (or Témiscaming) earthquake; the 1944 Cornwall–Massena earthquake; and the 1988 Saguenay earthquake. Although the magnitudes assigned to these earthquakes vary depending on the magnitude scale used, this report will refer to the magnitudes reported on the Seismicity Map of Canada, which are Charlevoix–Kamouraska, 6.7; Grand Banks, 7.2; Timiskaming, 6.2; Cornwall–Massena, 5.6; and Saguenay, 6.0 (Anglin et al. 1990).

3. The 1925 Charlevoix–Kamouraska earthquake

On February 28, 1925, at 21:19 Eastern Standard Time (March 1st at 02:19 Universal Time), an earthquake occurred in the Charlevoix–Kamouraska region and was widely felt as shown in Fig. 2. The ground shaking was felt south to Virginia, west to the Mississippi, east to the Atlantic, and north to 130 km north of Lake St. Jean. Damage was reported as far as Shawinigan, Quebec, some 250 km from the epicentre. Maximum intensity on the Rossi–Forel scale was IX (partial or total destruction of some buildings). Numerous aftershocks were felt locally in the weeks that followed (Smith 1962). The isoseismals of this earthquake, based on the Rossi–Forel (RF) intensity scale, are presented in Fig. 2.[1] Corresponding intensity values on the modified Mercalli (MM) intensity scale are currently being assessed by the Geological Survey of Canada.

Considerable damage was reported on the south shore of the St. Lawrence River near the epicentre. Fortunately, some of this damage was photographically documented. One such example is the Rivière-Ouelle church, located on thick clay

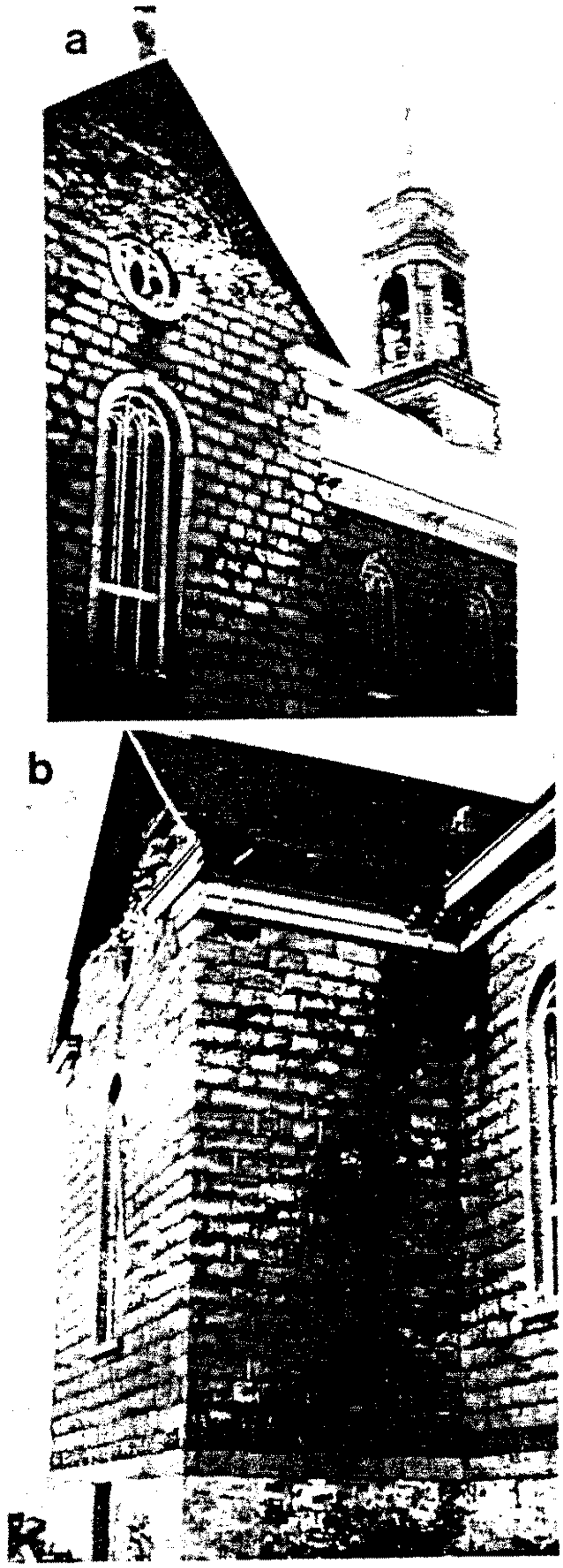

FIG. 3. Damage to Rivière-Ouelle's church (Hodgson, unpublished photo): (*a*) closeup view of out-of-plane failure of gable and in-plane shear cracks in walls; (*b*) side view of transept (Hodgson 1925).

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[1] Readers are referred to Richter (1958) for a description of these intensity scales. In general, MM VII and RF VIII represent the threshold value of damage to buildings, while MM III and RF III is the threshold below which an earthquake is rarely felt. Readers should be aware that isoseismal maps present area-averaged intensity values. Thus, it is possible a given location had damage corresponding to a higher intensity value than what is shown on the map.

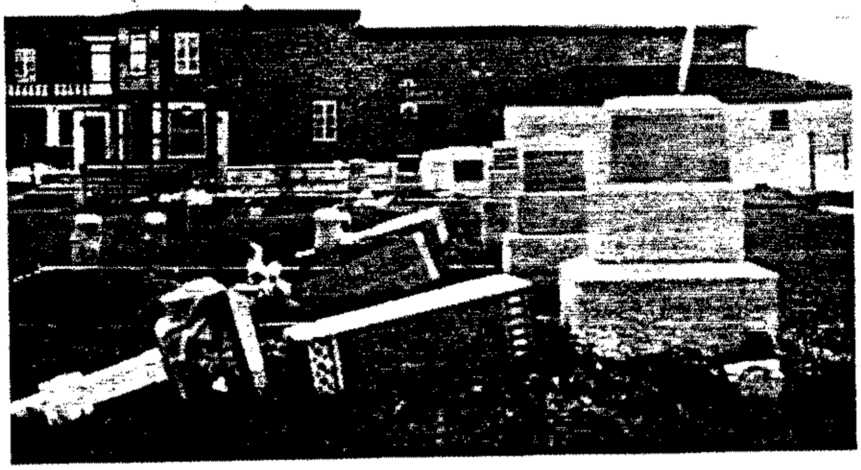

FIG. 4. Fallen monuments at Rivière-Ouelle's cemetery, located in the vicinity of the church. Photo taken 4–6 weeks after the earthquake (Hodgson 1925).

FIG. 5. Photo of Manoir Cabot east of La Malbaie on the north shore of the St. Lawrence River (Hodgson, unpublished photo) — in-plane shear failure of spandrel beams.

deposits (Figs. 3*a* and 3*b*). The out-of-plane failure of its unreinforced masonry gable, typical for this type of structures, is attributable to the lack and inadequacy of anchorage between the roof and walls and, in this particular case, to the lack of integrity between the wythes of an otherwise thick stone masonry wall. Some in-plane shear cracks in the walls are also visible. Contrary to what is stated in Hodgson (1925), the church was not demolished following the earthquake; repairs were made only to the damaged portions (Hudon 1972). In Rivière-Ouelle's cemetery, located in the vicinity of the church, most monuments fell (Fig. 4). Some cracks in clay deposits were also noticed nearby. Nearly all chimneys in the district were thrown down by the earthquake.

Although some structural damage was also reported to have occurred on the north shore, photographic evidence is scarce. Damage to Manoir Cabot is noteworthy; although hardly visible, some in-plane shear cracking occurred in spandrel beams of this residential masonry house near the epicentral region (Fig. 5). Hodgson (1950) reported important damage to this house including two chimneys at both ends of the house. Hodgson (1925) stated that the house was standing on a deep sand slope. Other buildings in the vicinity were not seriously damaged.

Little damage was reported in the city of Québec, approximately 150 km from the epicentre of the 1925 earthquake. In the lower town part of the city, structural damage occurred at the grain elevators and train terminal building (Gare du Palais); their location is shown in Fig. 6. This figure also demonstrates the low population density in this lower part of town at the time of the earthquake. All the agricultural lands shown are now covered by urban developments built mostly on top of the deep soft soils and clay deposits of the type known to amplify earthquake ground motions. Gare du Palais was, at the time, one of the few monumental buildings in the lower part of town. It was constructed of unreinforced masonry and steel trussed-arches spanning large open areas

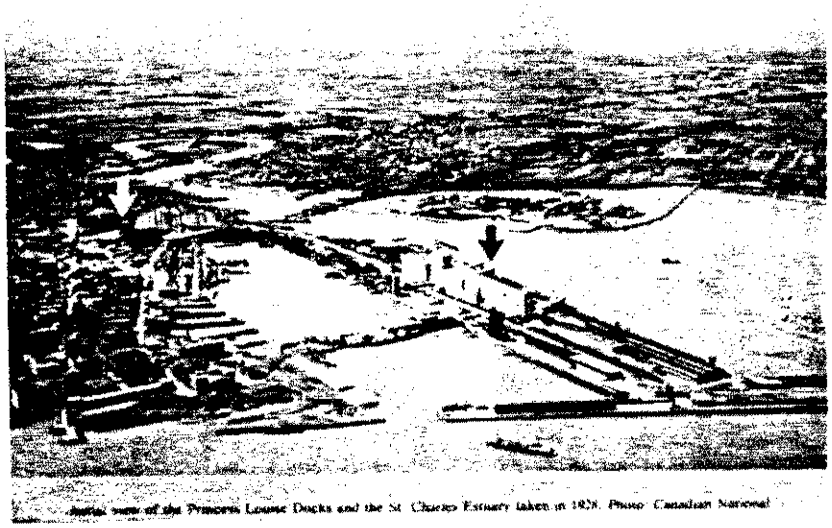

FIG. 6. The lower town part of Québec in 1928 showing the location of the grain elevators and train terminal building (Gare du Palais) (Canadian National Railways 1928).

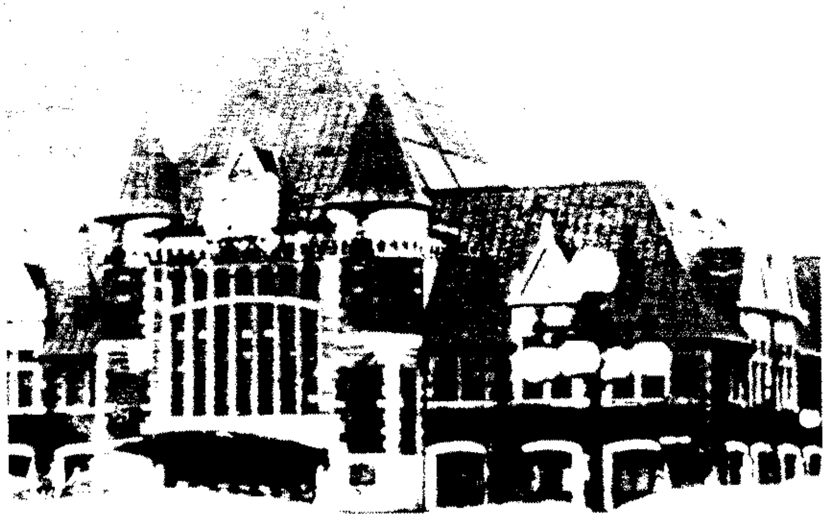

FIG. 7. Gare du Palais, Québec, about 150 km southeast of the 1925 epicentre (Hodgson, unpublished photo).

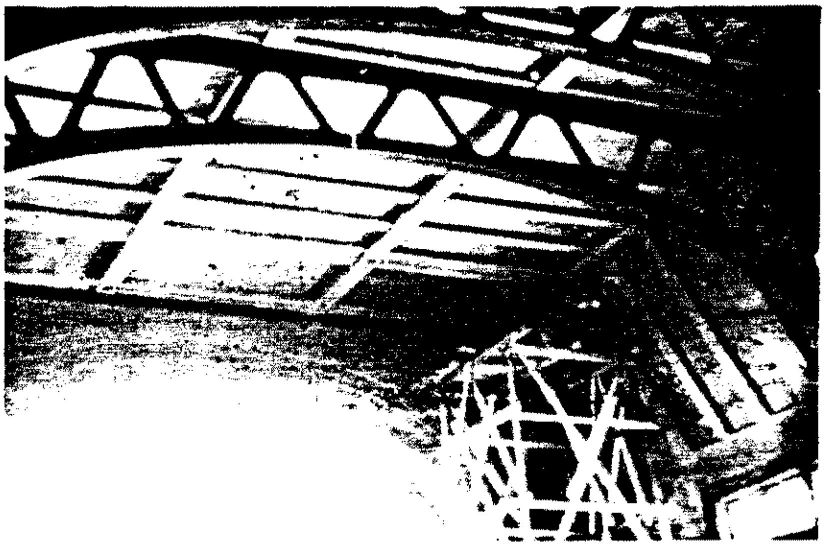

FIG. 8. Photo during repairs to walls of the Gare du Palais (Hodgson, unpublished photo).

FIG. 9. Displacement to supporting steel column of a freight shed in the Québec port (Hodgson 1925).

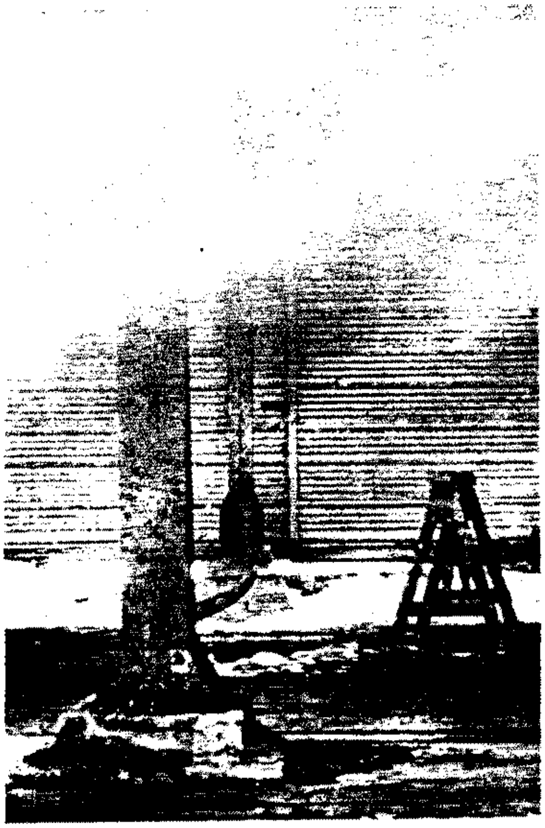

FIG. 10. Buckling of steel angle connecting the two steel columns supporting a span of the freight shed (Hodgson 1950).

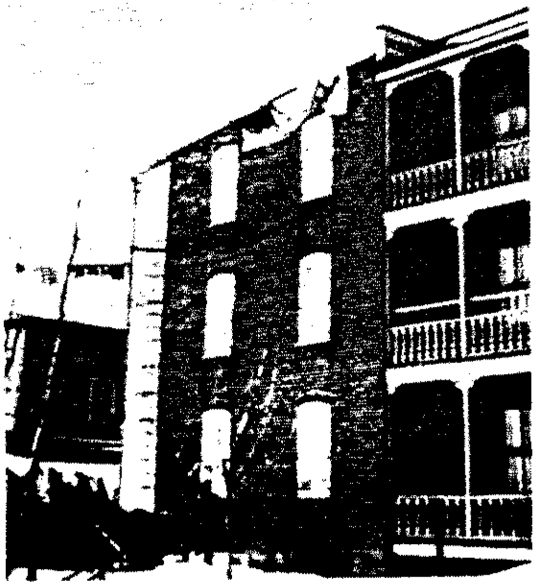

FIG. 11. Out-of-plane failure of unreinforced masonry wall in Shawinigan, approximately 250 km from the epicentre (Hodgson 1950).

(Fig. 7). While its walls were widely reported by local newspapers to have been damaged during this earthquake, the exact nature of the damage suffered by this building is not well documented. It is known that cracking developed above large windows in a waiting room, leading to the collapse of five rows of bricks into the concourse. Cracks also developed in many walls; and parts of the ceiling, skylight glass, and heavy lights fell. Yet, only a (somewhat disappointing) photograph taken during repairs could be found in photographic archives searched (Fig. 8). On the other hand, damage to the supporting steel columns of a freight shed in the port of the city of Québec is better documented. The column shown in Fig. 9 shifted by approximately 8 cm from its foundation because of motion and ground settlement. Many columns were reported to have settled by as much as 9 cm. Buckling of at least one steel angle connecting two steel columns supporting a span of the freight shed is documented (Fig. 10). Some other minor damage was reported, but most of the port facilities survived the earthquake intact. It is noteworthy that these port facilities were largely constructed on reclaimed land.

In Shawinigan, approximately 250 km from the epicentre, a few buildings suffered damage. In the absence of reported damage in similar structures between Québec and Shawinigan, soil amplification due to local geological conditions is probably responsible for part of this damage. Other causative factors noted in Hodgson (1950) from a report by Abbott (1926) are poor workmanship, shoddy material, insecure terrain, or improper design. Damage was essentially confined to the out-of-plane failure of unreinforced masonry walls and (or) their exterior wythe, as shown in Figs. 11 and 12. Out-of-plane failure of an unreinforced masonry transept

FIG. 12. Out-of-plane failure of unreinforced masonry wall in Shawinigan (Larochelle 1982).

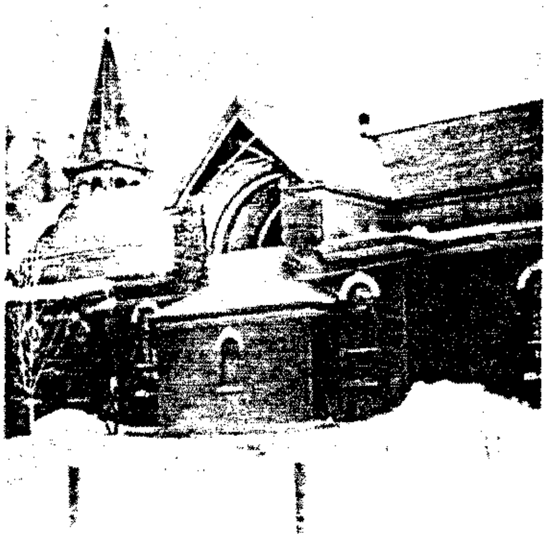

FIG. 13. Out-of-plane failure of unreinforced masonry transept wall of St. Marc Church in Shawinigan (Geological Survey of Canada archives).

wall of St. Marc Church in Shawinigan also occurred, as illustrated in a recently discovered photograph (Fig. 13). Clearly, the unreinforced masonry gable collapsed outwards, taking with it the stained-glass window and part of the exterior wythe of the masonry wall directly under that window.

It is noteworthy that the epicentre of the 1988 magnitude 6.0 Saguenay earthquake is clearly different from that of the 1925 Charlevoix–Kamouraska earthquake. However, some engineers still erroneously allege that all previous Charlevoix–Kamouraska earthquakes originated from the 1988 earthquake's epicentral region, with implications that, consequently, another period of "seismic-dormancy" of approximately 60 years has started immediately after the Saguenay earthquake's energy release. This is a myth, not a reality: all evidence demonstrates unambiguously that the two seismic regions are distinct, the Saguenay earthquake occurring some 40 km south of Chicoutimi in an area unrelated to the more active Charlevoix–Kamouraska seismic zone, as briefly substantiated in Appendix A.

4. The M7.2 1929 Grand Banks (or Laurentian Slope) earthquake

The Grand Banks earthquake occurred on November 18, 1929, at 20:32 Universal Time (16:32 Maritimes Standard Time, 17:02 Newfoundland Standard Time) and was felt throughout Newfoundland, the Maritime Provinces, eastern Quebec, and the northern New England States. Isoseismals of the Grand Banks earthquake (adapted by Smith (1966) from Doxsee (1948)), on the Rossi–Forel scale, are shown in Fig. 14. On land, damage due to earthquake vibrations was limited to Cape Breton Island (about 400 km epicentral distance) where chimneys were overthrown or cracked and where some highways were blocked by minor landslides. In addition, the earthquake was reportedly felt on two ships at sea near the epicentre (S.S. Caledonia and S.S. Olympic). The earthquake triggered a large submarine slump which ruptured 12 transatlantic cables and generated a tsunami (a large induced sea wave). The tsunami struck the southern end of the Burin Peninsula and the south end of Placentia Bay, claiming a total of 27 lives. Figure 15 shows a two-story house swept 3 km out to sea from Port au Bras, near Burin, southern Newfoundland. The house was subsequently recovered and secured to a Grand Banks fishing schooner which had safely ridden out the tsunami at this anchorage in Little Burin Harbour (background research by A. Ruffman, Geomarine Associates Ltd., Halifax).

5. The M6.2 1935 Timiskaming earthquake

On November 1, 1935, at 06:03 Universal Time (01:03 local time), an earthquake took place in the vicinity of Timiskaming, Quebec. This earthquake was felt west to Thunder Bay, Ontario (then named Fort William), east to the Bay of Fundy and south to Kentucky and Virginia. Damage to houses was reported as far as Mattawa and North Bay, some 70 km from the epicentre. An isoseismal map of the Timiskaming earthquake, on the modified Mercalli scale, is shown in Fig. 16 (Smith 1966). In Timiskaming, Quebec, Hodgson (1936*b*) reported that, as illustrated in Fig. 17, about 80% of all chimneys were damaged, which is one of the elements used to give a maximum intensity of VII on the modified Mercalli scale (cracked chimneys to

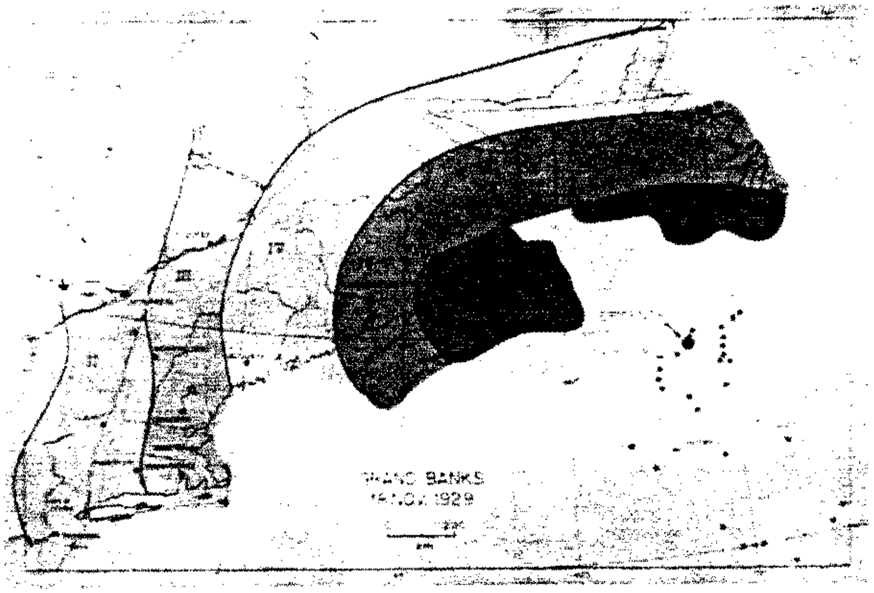

FIG. 14. Isoseismal map of the 1929 Grand Banks earthquake on the modified Mercalli scale (adapted by Smith (1966) from Doxsee (1948)).

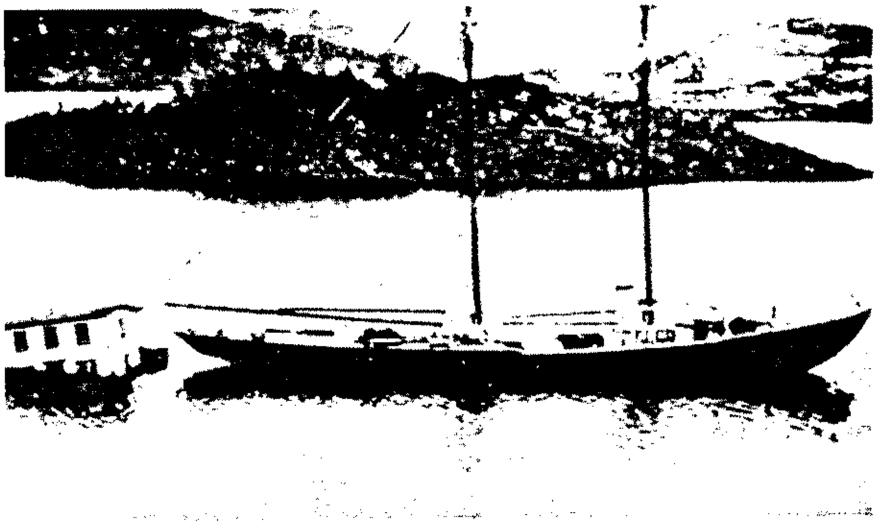

FIG. 15. Two-story house swept to sea by the 1929 tsunami, and subsequently recovered and secured to a Grand Banks fishing schooner (still and moving image collection of the Public Archives of Newfoundland and Labrador, 1929, St. John's, Newfoundland).

considerable extent). In addition, cracks developed in some solid brick walls. Timiskaming houses were relatively well constructed and kept in good repair which, in addition to the near-surface bedrock, minimized damage (Hodgson 1950). In Mattawa and North Bay (both about 70 km from the epicentre), many chimneys were thrown down (Hodgson 1945*a*). In the epicentral region, minor rock falls were observed, as well as cracks in the gravel and sand at the edges of islands and borders of lakes. In the months that followed the earthquake, numerous aftershocks were felt in Timiskaming and Kipawa.

Some 300 km away from the epicentre, near Parent, Quebec, earthquake vibrations triggered a 30 m slide of railroad embankment (Figs. 18 and 19). Delicately balanced rocks nearby were interpreted by Hodgson (1936*b*) as evidence that the sliding was already imminent at the time of the earthquake.

6. The M5.6 1944 Cornwall–Massena earthquake

On September 5, 1944, at 04:38 Universal Time (12:38 local time), an earthquake occurred near the towns of Cornwall, Ontario, and Massena, New York. The felt area extends north to south from the Abitibi to Virginia and east to west from New Brunswick to Lake Michigan. Damage was restricted to about 50 km from Cornwall. Many aftershocks were felt locally in the weeks that followed (Smith 1966). The isoseismal map of the Cornwall–Massena earthquake, on the modified Mercalli scale, is shown in Fig. 20.

Although this earthquake was only of magnitude 5.6, it caused considerable damage in both Cornwall and Massena (Hodgson 1945*b*). About 2000 chimneys were damaged in Cornwall alone, which is one of the elements used to assign an intensity VII rating on the modified Mercalli scale. Outwash sand and marine clay areas were found to correlate with regions of maximum damage (Berkey 1945). Damage

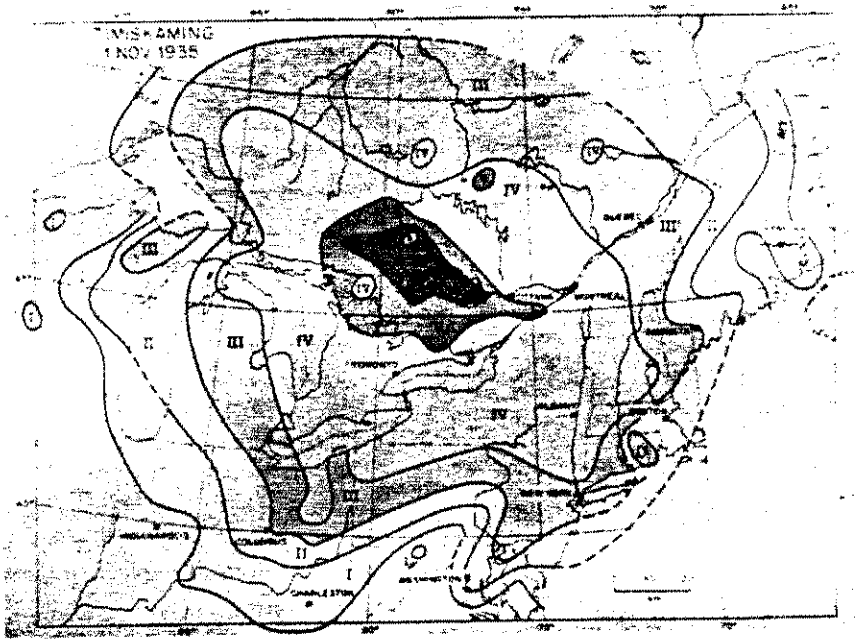

FIG. 16. Isoseismal map of the 1935 Timiskaming earthquake (modified Mercalli scale) (Smith 1966).

estimates were of the order of $600 000 for Cornwall (population of 15 000 in 1944) on property value estimated at $11.5 millions (Sweet 1944). Typically, damage consisted of out-of-plane failures of veneers, top-walls, and exterior wythes of multi-wythes walls, chimney failures, and some in-plane cracking.

Considerable damage was caused at the Collegiate and Vocational School, a two-story-and-basement brick building located in Cornwall. The out-of-plane failure of the unreinforced masonry wall at the top story of a wing of this college was considerable and surprising, considering the small magnitude of this earthquake (Fig. 21). The falling masonry broke through the roof of the adjacent gymnasium, damaging it badly (Fig. 22). Out-of-plane failure of the unreinforced masonry veneer of an apartment building in Cornwall (Fig. 23) also occurred. At another two-story unreinforced masonry house in Cornwall, the top section of its second story brick wall failed out-of-plane, collapsing inward (Fig. 24). Finally, spectacular damage to a two-story residential unreinforced masonry dwelling in Cornwall was photographically documented (Figs. 25 and 26); there, the exterior wythe of walls having multi-wythes improperly bonded along their collar joint failed out-of-plane, with some inplane shear cracks also visible. The County Court House and Orange Block buildings reportedly also developed similar bulges of several inches in their unreinforced masonry walls (Legget 1944; Sweet 1944).

FIG. 17. Bulged chimney, 1935 Timiskaming, Quebec (Hodgson 1936*b*).

7. Minor damage due to small earthquakes 1973–1982

Between the time of the Cornwall–Massena earthquake (1944) and the Saguenay earthquake (1988) at least three small eastern Canadian earthquakes caused minor damage in their respective epicentral regions. These events were the 1973 magnitude 4.9 Woburn, Quebec, earthquake (Wetmiller 1975), the 1979 magnitude 5.0 Charlevoix earthquake (Hasegawa and Wetmiller 1980) where chimney damage was reported in the epicentral regions, and the two 1982 magnitude 5 Miramichi earthquakes which caused minor damage (widening of wall cracks) up to distances of 100 km (Pernica and Maurenbrecher 1982).

8. The M6.0 1988 Saguenay earthquake

On November 25, 1988, at 18:46 Eastern Standard Time, the Saguenay earthquake occurred in the Laurentide Wildlife Reserve, some 35 km to the south of the city of Chicoutimi,

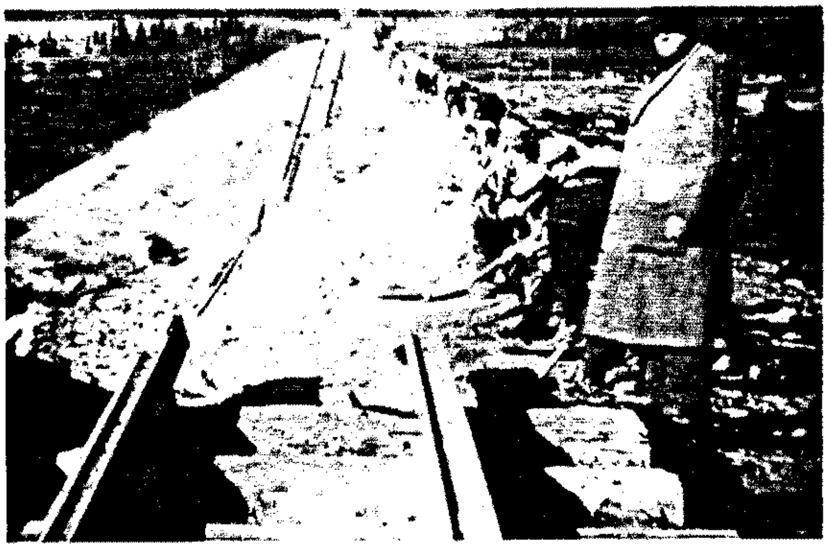

FIG. 18. Slide of railroad embankment near Parent, Quebec, some 350 km from the epicentre (photo by Canadian National Railways, Geological Survey of Canada archives).

FIG. 19. Slide of railroad embankment near Parent, Quebec, some 350 km from the epicentre (photo by Canadian National Railways, Geological Survey of Canada archives).

Quebec, and 100 km north of the city of Québec. This earthquake presents many intriguing characteristics: its location in a hitherto relatively aseismic region, its depth in the lower crust, its large component of high-frequency seismic waves, its remarkably mild aftershock activity, and the difficulty of defining the reactivated geological structure (North et al. 1989). The felt area exceeded 3.5 million km^2 (maximum intensity MM VIII indicated by fallen tombstones and liquefaction features) (Cajka and Drysdale 1993) and closely approached that of the larger 1925 Charlevoix–Kamouraska earthquake. The earthquake was felt south to Washington, D.C., north to Poste-de-la-Baleine, Quebec, east to Goose Bay and Halifax, and west to Thunder Bay and the state of Illinois. The isoseismal map of this earthquake, on the modified Mercalli scale, is shown in Fig. 27.

The earthquake caused isolated cases of property damage in the Saguenay region and in the metropolitan areas of the city of Québec (average intensity of the region of VI) and Montreal (average intensity of the region of V) (Mitchell et al. 1990). Most of the reported damage was of a nonstructural nature, including cracked or partially collapsed nonbearing masonry walls, cracked and collapsed chimneys, fallen ceiling tiles, etc., as, for example, presented in Figs. 28 and 29. In some cases, damage was attributable not only to the initial strength of the ground shaking but also to the poor condition of structures or their foundations. Some isolated unreinforced masonry failures, such as the out-of-plane collapse of a gable at the Hippodrome de Québec (Fig. 30), have been spectacular. Disturbances to lifeline facilities were also reported; for example, electrical hardware of some transformer stations of Hydro-Québec suffered significant damage (Pierre 1989). Fortunately, as the epicentre was in the middle of a wildlife reserve, remote from major urban centres, the total cost for all damage caused by the earthquake in the province of Quebec is estimated to have not exceeded few tens of million dollars.

Additional seismological information on the Saguenay earthquake can be found in North et al. (1989) and Du

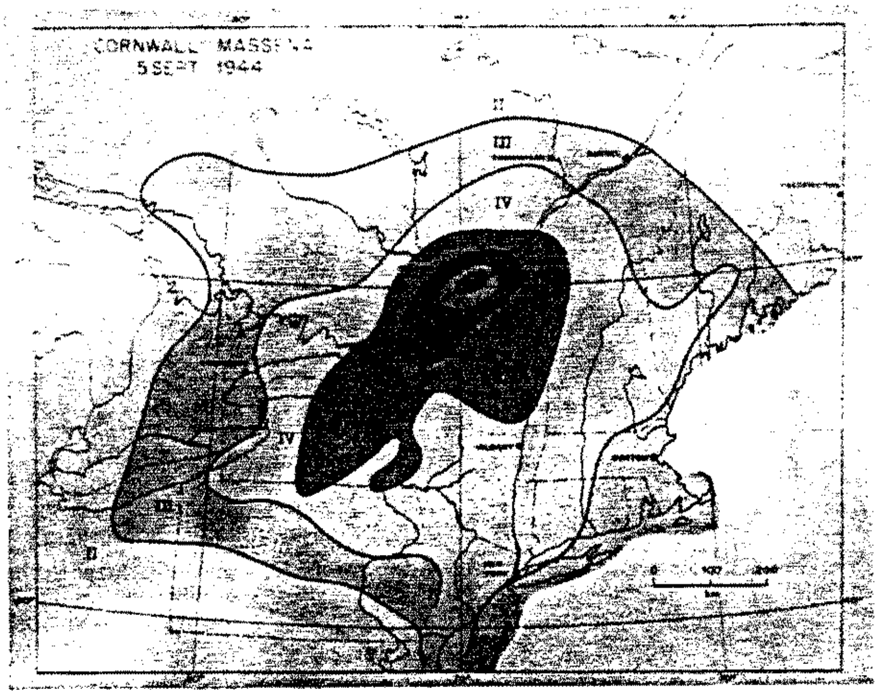

FIG. 20. Isoseismal map of the 1944 Cornwall–Massena earthquake (modified Mercalli scale) (Smith 1966).

FIG. 21. Damage at the Collegiate and Vocational School, Cornwall (Sweet 1944) — out-of-plane failure of masonry wall.

Berger et al. (1991); strong motion records in Munro and Weichert (1989); and damage reports and interpretation in Mitchell et al. (1989, 1990) and Allen et al. (1989).

9. Failure modes of unreinforced masonry buildings during earthquakes

Clearly, the majority of the buildings damaged by the above earthquakes were of unreinforced masonry construction. However, the reported types of damage were but a subset of all known potential modes of failure of unreinforced masonry buildings during earthquakes. These various typical failure mechanisms are briefly reviewed below, to provide the reader with a better appreciation of the nature and severity of damage in the above eastern Canadian earthquakes, and to provide a summary of all structural deficiencies which must be addressed and corrected in seismic rehabilitation works on unreinforced masonry buildings.

In many unreinforced masonry buildings, there is a total absence of positive anchorage of the floors and roof to the unreinforced masonry walls. In these buildings dangerously lacking structural integrity, many structural components rely on contact and friction to transfer gravity and lateral forces. Thus, beyond a certain threshold of seismic excitation, the various structural elements risk to separate and behave independently during an earthquake. Typically, exterior walls can behave as cantilevers over the total building height and fail in an out-of-plane manner, or global structural failure can occur by slippage of the joists and beams from their supports. While visible separation of walls and floors has sometimes been reported in the existing literature after past

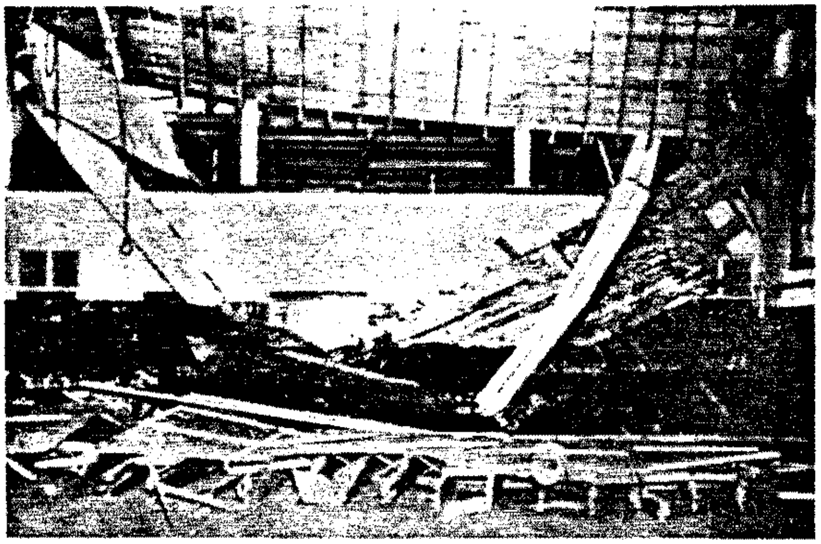

FIG. 22. Damage at the Collegiate and Vocational School, Cornwall (Cornwall Daily Standard-Freeholder 1944).

FIG. 23. Out-of-plane failure of the unreinforced masonry veneer of an apartment building in Cornwall (Sweet 1944).

FIG. 24. Unreinforced masonry out-of-plane failure, top part of a wall, residential building in Cornwall (Sweet 1944).

FIG. 25. Damage to a two-story residential unreinforced masonry dwelling in Cornwall (Berkey 1945) — in-plane shear cracks and out-of-plane failure of multi-wythe wall due to inadequate collar joint are visible.

eastern Canadian earthquakes (e.g., damage to Manoir Cabot (Hodgson 1950)), photographic evidence has not been found.

Although joists-to-walls anchors can sometimes be found in unreinforced masonry buildings, their presence is often unrelated to seismic concerns, and their failure likely during an earthquake. Typically, the metal of the anchor may fail, or the anchor could shear loose from the framing member at one end or be pulled off the masonry at the other end. The details of these modes of rupture obviously vary with the type of anchors used, but, in most cases, damage is hidden or overlooked by the untrained eye.

Excessive bending or shear may produce in-plane failures and familiar through-thickness cracks in masonry walls. In many cases, these more common cracks are overshadowed by simultaneous more spectacular type of failures, but nonetheless present (Figs. 3*b* and 25). For unreinforced masonry walls, in-plane shear failures are more common, as expressed by diagonal shear cracking. Fortunately, until the shear cracks become unduly severe, the gravity-load-carrying capacity of the walls is not jeopardized. In masonry facades having numerous window openings, spandrels and the short piers between them may also fail in shear (Fig. 5). Flexural failure is also possible for more slender unreinforced masonry elements (Fig. 29).

Unreinforced masonry buildings are most vulnerable to flexural out-of-plane failure (Figs. 3*a*, 11, 12, 21, 22, and 24). Moreover, the unstable and explosive-like out-of-plane failure of unreinforced masonry walls can endanger the gravity-load-carrying capabilities of a wall and can seriously injure or kill occupants and passersby. Note that out-of-plane failure may occur even if joist-to-wall anchors are present in sufficient numbers and strength to provide out-of-plane support to the walls at each floor and roof level, as demonstrated elsewhere (Bruneau 1994). Nonstructural elements, such as parapets, gables of churches and other buildings, and other elements extending beyond the roof line, can also fail in an out-of-plane manner, creating severe life-safety hazards (Figs. 3*a*, 13, and 30). Similarly, chimneys, also located at the top of buildings where the greatest amplification of the ground motions occurs, are often toppled with potentially lethal consequences.

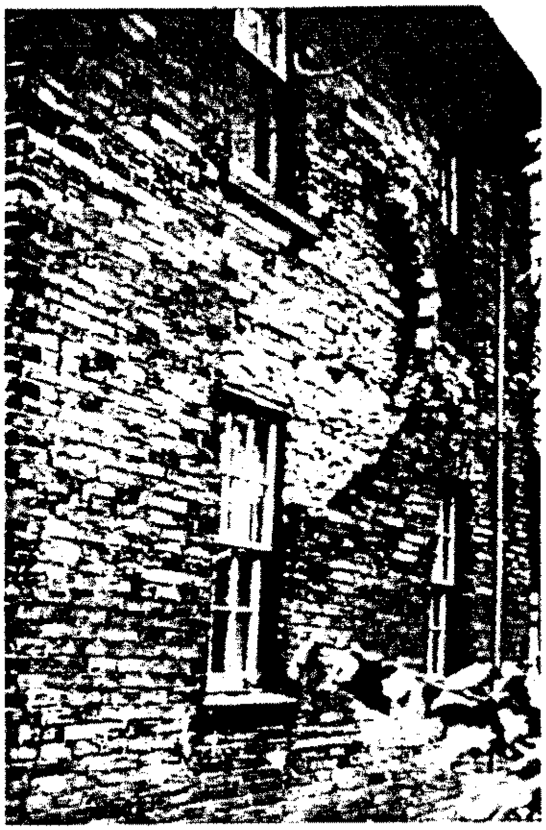

FIG. 26. Damage to opposite side of the two-story residential unreinforced masonry dwelling of Fig. 25 (Berkey 1945).

When the mortar of collar joints is either absent, discontinuous, or of poor quality, multi-wythe walls are extremely vulnerable to seismic excitation. With each wythe behaving independently as an individual thin wall, the exterior layers will usually fail first as they are less effectively connected to any other structural components (Figs. 25 and 26). By analogy, this is also true for unreinforced masonry veneers (Fig. 23).

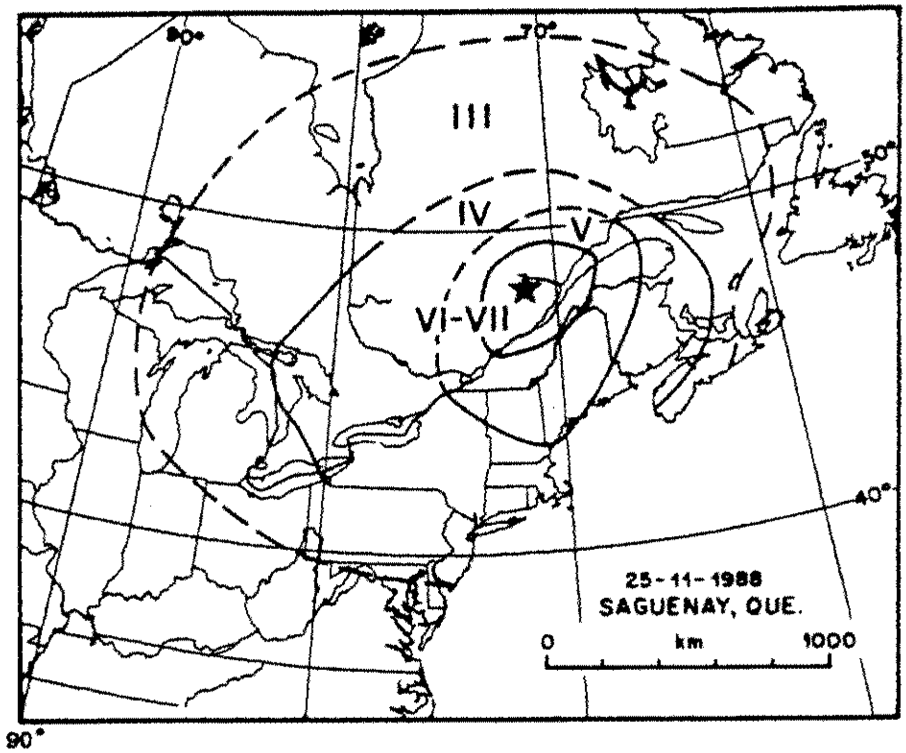

FIG. 27. Isoseismal map of the 1988 Saguenay earthquake (modified Mercalli scale) (Cajka and Drysdale 1993).

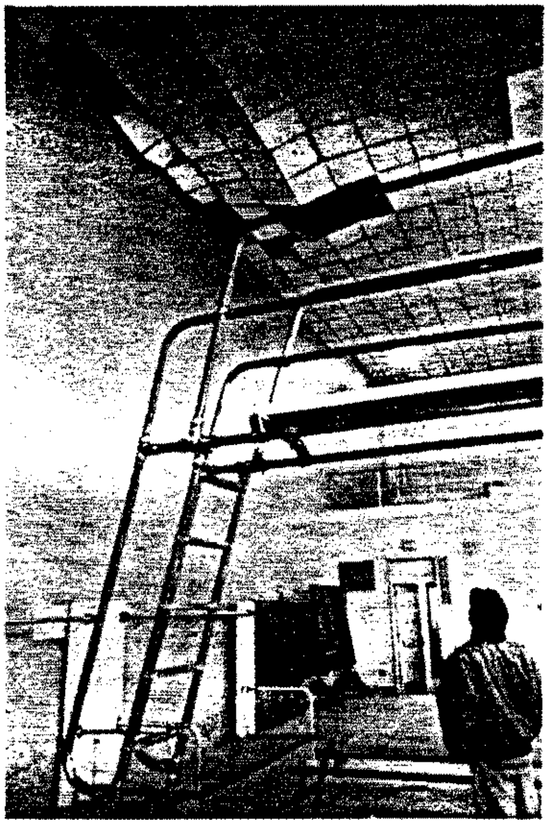

FIG. 28. 1988 Saguenay earthquake; partial collapse of non-structural ceiling tiles, swimming-pool hall, Ecole Wilbrod Bhérer, Québec (Gilles Fréchette, personal communication).

Earthquake forces are multidirectional in nature, and thus each unreinforced masonry element is solicited in both its in-plane and out-of-plane directions. In-plane shear cracking, which can produce triangular cantilever wedges, can therefore help precipitate out-of-plane failure of the weakened wall. Pounding against adjacent structures can further accelerate this combined failure mode, particularly for the many old North American unreinforced masonry buildings built without adequate separation. However, on-site identification of this combined failure mode is difficult, and such failures are generally be attributed uniquely and erroneously to the sole effect of out-of-plane forces.

Failure of the floor diaphragms has rarely been observed following earthquakes. This could be attributable, partly, to the tendency of earthquake reconnaissance teams to mostly report observations as made from the exterior of buildings, inside inspections made for insurance and repair purposes are generally strictly confidential. In eastern Canada, photographic documentation of diaphragm failures, or typical diaphragm-induced failures in wall corners, has not been found by the authors.

10. Vulnerability of existing unreinforced masonry buildings

Existing unreinforced masonry buildings have long been recognized as the structures most vulnerable to earthquakes. The loss of life attributable to their collapse during earthquakes is well documented in other countries. However, awareness of the risks they pose is relatively new in eastern Canada. As this type of construction is prevalent in the downtown core of most North American cities, the districts usually of highest population density, the magnitude of this seismic risk is appreciable.

Clearly, the occupants of unreinforced masonry buildings face three options: (*i*) do nothing and wait, obviously in the belief that no earthquake of killing potential will occur; (*ii*) move out; (*iii*) persuade the owner of the necessity to seek

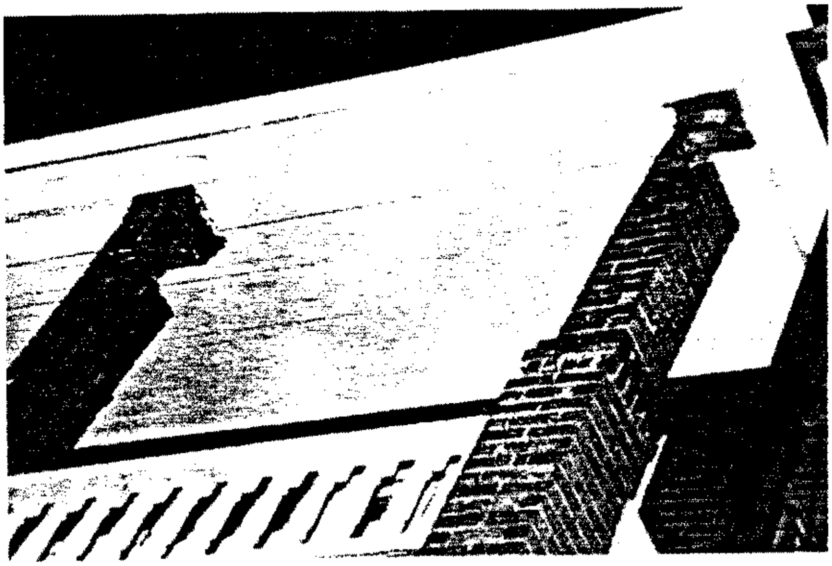

FIG. 29. 1988 Saguenay earthquake; flexural failure of unreinforced masonry pilaster, multi-units residential building in downtown Québec (Gilles Fréchette, personal communication).

engineering advice regarding the seismic adequacy of the building, and to perform whatever seismic-retrofitting works necessary. Obviously, owners who are also the occupants are more likely to be convinced in the latter case. Yet, all three options are acceptable, and in some cases justified, provided the concerned parties are willing to live with the consequences of their decision on life-safety (obviously, in a societal sense, employees, customers, or passersby are also concerned parties).

When structural engineers are retained to investigate the seismic resistance of various unreinforced masonry facilities, they quickly discover the limitations of the current masonry standards whose simplistic design guidelines are of little, if any, assistance in formulating a realistic assessment of this resistance. Appraisal of the seismic adequacy of an unreinforced masonry building is a particularly intricate assignment in an eastern North American context. In the absence of legislation prescribing how, or on which basis, this structural assessment is to be accomplished, engineers must establish both. At first, this may appear to the designer as an ideal situation. However, in eastern North America, the long return period of damaging earthquakes, the absence of interim seismic activity, and (or) the often small to moderate predicted intensity of earthquakes having probabilities of occurrence equal to (or sometimes even smaller than) those used to derive building codes seismic maps, shed a new and different perspective on the problem. For example, the real "threshold" of damage of a given unreinforced masonry structure may be only slightly exceeded during an earthquake with short duration of strong motion of, say, magnitude 6.0, but a conventional engineering assessment based on code procedures would not only be incapable of predicting this satisfactory performance, but likely label the building as seismically unsafe.

Furthermore, many owners currently concerned with the mitigation of seismic risks in eastern North America are public and private agencies staffed with engineers, and are quite capable of dismissing engineering evaluations lacking credibility, i.e., based on too conservative or liberal modelling and analytical assumptions. The structural engineer who operates in that context must ethically reconcile his professional responsibility and understanding of the seismic performance of unreinforced masonry buildings with the owner's perception of seismic safety, while remaining competitive. Some engineers have expressed fears regarding the large potential liabilities involved in dealing with seismically deficient unreinforced masonry buildings, and have elected to completely avoid any involvement in such work until a clear legal framework is available. Others, on the contrary, have raised to the challenge (e.g., Knoll 1983, 1991).

In that context, the potential benefits ensuing from the development of better tools to accurately determine the true seismic resistance of unreinforced masonry structures can be appreciated. Toward that objective, a large research effort is under way internationally (Bruneau 1994). Also, a detailed seismic evaluation procedure has already been formulated based on some relatively recent findings on the seismic performance of unreinforced masonry buildings (ABK 1984), and has been adopted by numerous model-code documents and guidelines in the U.S.A. (FEMA 1992*a*; ICBO 1991) and Canada (NRC 1992*a*). This new methodology is reviewed elsewhere (Bruneau 1994). Research is also under way at the University of Ottawa to enhance knowledge on the seismic performance of unreinforced masonry buildings and develop methods to assist the engineers involved in their evaluation and retrofit; presentation of the findings will be reported in a subsequent paper.

11. Mitigation of seismic risks

The technological advancement of a society is partly judged by its self-sufficiency and capable response when facing rare and potentially devastating environmental events. Countries that need not seek external assistance following the passage of a tropical storm, or that are not disrupted beyond recovery by an earthquake, have a more positive image and are generally attractive to investors. Indeed, there are potential tangible benefits in acknowledging the existence of seismic risks, taking actions to mitigate them, and planning for future postdisaster recovery. For example, following the 1989 Loma Prieta earthquake, economic activities in San Francisco resumed just a few days following the earthquake, and most of the structural damage was repaired in less than

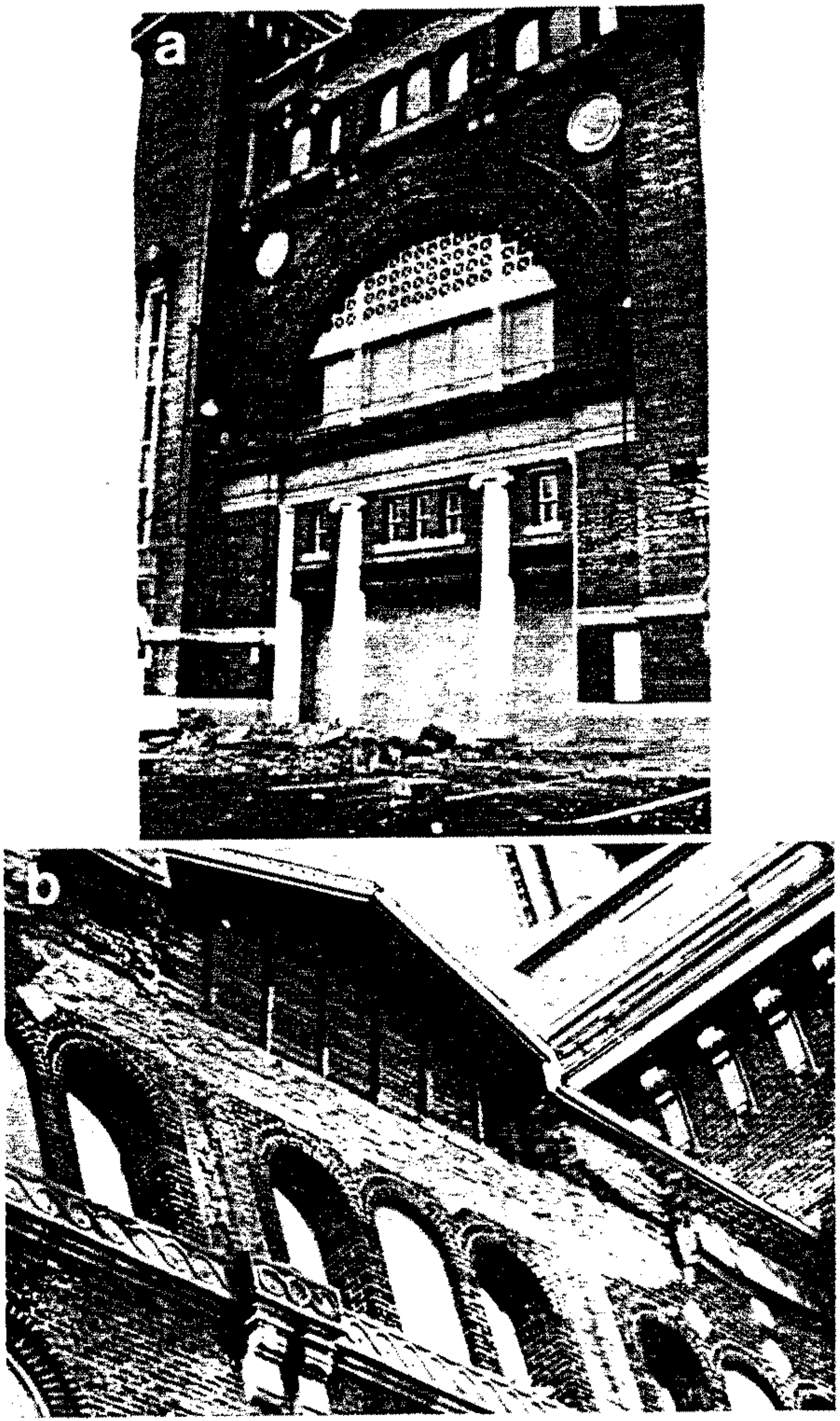

FIG. 30. 1988 Saguenay earthquake; out-of-plane failure of unreinforced masonry gable, Hippodrome de Québec: (*a*) global view; (*b*) closeup view (photos by first author).

a year. It is noteworthy that San Francisco enacted a parapet-retrofit ordinance years earlier, and long rehearsed postdisaster scenarios. By contrast, just across the San Francisco Bay, in Oakland, most of the damaged buildings remained unrepaired and (or) abandoned 2 years after the earthquake (Look 1991). The Oakland City Hall was one such abandoned building awaiting repairs, at a huge interim cost to its citizens, not to mention the irreparable damage to the city's image, which has since suffered considerably from comparison with neighbouring San Francisco.

Worldwide, eastern Canadian citizens are amongst those with the least amount of earthquake awareness and preparedness relative to the high seismic risk that prevails. In fact, most Canadians are almost totally ignorant of what they could and should do to reduce seismic risk. A coordinated eastern Canadian programme of seismic-risk mitigation is long overdue.

Past experience has demonstrated that the establishment of programmes and priorities for the seismic rehabilitation of buildings is nearly impossible when a community lacks basic seismic awareness. Even for communities understanding the seismic risk, successful implementation of a seismic-risk mitigation policy apparently requires, to various degrees, a prominent inside leader within the concerned municipal policy-making body, media attention and support, financial incentives, a long-term earthquake forecast with property damage and injury and death scenario for this future event, legislated inducement to action (by ordinances or acts) from a higher government level, and a clear understanding of the scope and flexibility of that policy and the liabilities involved (FEMA 1989). Information on the political and economical difficulties posed by such agendas is available in the existing literature (e.g., Alesch and Petak 1986; FEMA 1989). The above nonetheless suggests that implementation can only be successful if planning starts at the municipal level, in a community educated about its exposure to seismic risks.

For any given city in eastern North America having a large inventory of older structures and infrastructure never or deficiently designed to resist earthquakes (such as unreinforced masonry buildings), a tentative scenario to enhance seismic-risk awareness (the first step in any seismic-risk mitigation programme) proceeds as follows:

- Evaluation of the overall effects on that city and surrounding communities of a major earthquake within the range of magnitudes realistically expected to occur there. This evaluation, ideally coordinated by a specially mandated task group, including participation by all government levels, should broadly address all possible scenarios, e.g., earthquake in winter (subzero temperature, heavy snow) or at the height of the tourism season, and take into account engineering factors of demonstrated importance such as local construction types and soil conditions. Available procedures for estimating losses (FEMA 1989; APT 1985) should be used to assess direct and indirect costs. Typically, direct costs provided by such methodologies include the cost of earthquake damage and repairs, and the projected number of injuries and casualties. Indirect costs encompass housing losses, business losses, unemployment, tax impact, and probable delays until normal economic activities can resume in the affected zones. Loss estimates have already been conducted for various cities throughout the United States, such as Los Angeles (Algermissen et al. 1973), Salt Lake City (USGS 1976), St. Louis (FEMA 1990), to name a few, and have provided most valuable information for the development and evaluation of seismic-risk mitigation policies.
- Communication of the results of this evaluation to the responsible officials and the general population, for each pre-established scenario.
- Education and related activities to enhance the awareness of the general public, including engineers, municipal and provincial civil servants and planners, politicians, and other municipal and provincial decision makers.

Without this broad-based awareness of the seismic risk and potential losses, any mitigation policy is doomed to fail. Once popular support (and subsequently political will) develops for seismic-risk mitigation activities, many courses of action are possible.

- Municipalities can contemplate various seismic-risk policies. The merits of minimum, voluntary, and mandatory programmes are presented elsewhere (FEMA 1989). In many instances, at the municipal level, seismic-risk mitigation programmes have targeted the rehabilitation of existing unreinforced masonry buildings as the most urgent issue.
- Individual owners may also elect to review the seismic resistance of individual building or entire inventory of structures.
- A comprehensive seismic-risk mitigation programme can be enacted. This would first require (with the assistance of structural engineers) the identification and evaluation of seismic risk to buildings and infrastructures (transportation, communications, etc.), and clearly state the responsibility of each participant (population, municipalities, province) and its role to ensure a successful implementation of this programme.

Existing cost–benefit models for the seismic rehabilitation of buildings (FEMA 1988, 1992*b*) can be of great assistance. An extensive literature on seismic evaluation and rehabilitation (NRC 1992*a*, 1992*b*; FEMA 1992*a*, 1992*c*; Bruneau 1994) can be of assistance to structural engineers involved in the mitigation of hazardous conditions created by existing buildings, unreinforced masonry and others.

In all cases, the decision to act (or not) and mitigate the identified risks remains a political option largely affected by the available financial resources and the conviction and sincerity of the previously identified political will. Nonetheless, the implementation of at least one of these steps would already be a significant improvement over the current situation, and could translate into direct human or monetary savings during the next major Canadian earthquake. It is noteworthy that, very recently, some of the above suggested actions have already been taken in British Columbia (Robbin Tom, Emergency Preparedness Canada, Vancouver, personal communication; IBC 1993; Pierce 1993; PEP 1992; EPC 1993). Hopefully, this may inspire eastern Canadians to reexamine their attitude towards these issues.

12. Conclusions

In the past, destructive earthquakes have occurred in eastern Canada, and similar events will undoubtedly recur in the future. The present review has stressed several lessons useful for seismic hazard and seismic risk studies.

Moderate to large eastern Canadian earthquakes can be felt over large distances and damage is not constrained to the epicentral region. Surprisingly, earthquakes of magnitude as low as 5.6 can cause considerable damage to structures in the close epicentral region, as demonstrated by the 1944 Cornwall earthquake, and more recently elsewhere by the Newcastle, Australia, magnitude 5.5 earthquake of 1990 (Perry 1990).

Although none of the events that occurred on land (1925, 1935, 1944, 1988) caused a surface rupture, two of them induced earth slides at considerable distance from the epicentre. As for offshore earthquakes, the 27 victims of the earthquake-induced tsunami of 1929 constitute a reminder of this important hazard along the eastern seaboard.

The Canadian earthquakes reviewed herein produced severe damage to unreinforced masonry buildings. Although written accounts for the older seismic events, generally made by nonengineers (with few exceptions), are often incomplete for thorough engineering studies, photographic documentation can be used as a useful preliminary assessment of this type of structural damage. From this evidence, out-of-plane failure has been the most frequently reported form of damage to unreinforced masonry buildings, in agreement with current knowledge on the behaviour of such structures. However, the often spectacular aspect of out-of-plane failures is also partly responsible for the high attention they received in past eastern Canadian earthquakes. Evidently, this type of damage, even if nonstructural, can injure, maim, or kill.

A large number of buildings and structures built in the first part of the century, i.e., prior to earthquake-resistant design, still exist in eastern Canada. Thus, structural damage at least similar to that described above is likely to recur during comparable future earthquakes, particularly if they occur near a major urban area. Moreover, much of the recent urban and industrial development is on soils now recognized as capable of amplifying earthquake ground motions. Both these factors make structural damage a much more severe and generalized risk than impressed in this report.

Acknowledgments

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Abbott, C.D. 1926. The St. Lawrence earthquake of February 28, 1925 — its effects on structures at Three Rivers and Shawinigan Falls, P.Q. Inspection Department of the Associated Factory Mutual Fire Insurance Companies, Boston, Mass., Report.

ABK. 1984. Methodology for mitigation of seismic hazards in existing unreinforced masonry buildings: the methodology. ABK-TR-08, Agbabian & Associates, S.B. Barnes & Associates, and Kariotis & Associates, El Segundo, Calif.

Adams, J.E., and Basham, P.W. 1989. The seismicity and seismotectonics of Canada east of the Cordillera. Geosciences Canada, **16**(1): 3–16.

Alesch, D.J., and Petak, W.G. 1986. The politics and economics of earthquake hazard mitigation — unreinforced masonry buildings in southern California. Institute of Behavioral Sciences, University of Colorado, Boulder, Colo.

Algermissen, S.T. et al. 1973. A study of earthquake losses in the Los Angeles, California area. Federal Disaster Assistance Administration, Washington, D.C.

Allen, D.E., Fontaine, L., Maurenbrecher, A.H.P., and Gingras, M. 1989. The Saguenay earthquake: damage to masonry construction. Institute for Research in Construction, National Research Council Canada, Ottawa, Ont., Report 584.

Anglin, F.A., Wetmiller, R.J., Horner, R.B., Rogers, G.C., and Drysdale, J.A. 1990. Seismicity map of Canada. Geological Survey of Canada, Canadian Geophysical Atlas, Map 15, scale 1:10 000 000.

ATC. 1985. Earthquake damage evaluation data in California. Applied Technology Council, Redwood City, Calif., Report ATC-13.

Basham, P.W. 1987. Seismic hazards assessment and seismic codes for eastern Canada. Proceedings of the symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America, National Center for Earthquake Engineering Research, State University of New York, Buffalo, N.Y., Report 87-0025, pp. I-1 to I-15.

Basham, P.W., Weichert, D.H., Anglin, F.M., and Berry, M.J. 1982. New probabilistic strong ground motion maps of Canada: a compilation of earthquake source zones, methods and results. Earth Physics Branch, Ottawa, Ont. Open File No. 82-33.

Berkey, C.P. 1945. A geological study of the Massena–Cornwall earthquake of September 5, 1944 and its bearing on the proposed St. Lawrence River project. United States Engineer Office, Internal Report.

Bruneau, M. 1992. Myths and realities of earthquake resistant design in Québec. Proceedings of the Canadian Society for Civil Engineering Annual Conference, Québec, Que., Vol. IV, pp. 225–234. (In French.)

Bruneau, M. 1994. Seismic evaluation of unreinforced masonry buildings — a state-of-the-art report. Canadian Journal of Civil Engineering, **21**(3): 512–539.

Cajka, M.G., and Drysdale, J.A. 1993. Intensity reports of the November 25, 1988 Saguenay earthquake. Geological Survey of Canada, Ottawa, Ont. Open File Report.

Dewey, J.W., and Gordon, D.W. 1984. Map showing recomputed hypocentres of earthquakes in the eastern and central United States and adjacent Canada, 1925–1980. U.S. Geological Survey, Miscellaneous Field Studies Map MF-1699.

Doxsee, W.W. 1948. The Grand Banks earthquake of November 18, 1929. Publications of the Dominion Observatory, Ottawa, **7**(7): 323–335.

Du Berger, R., Roy, D.W., Lamontagne, M., Woussen, G., North, R., and Wetmiller, R.J. 1991. The Saguenay (Quebec) earthquake of November 25, 1988: seismological data and geological setting. Tectonophysics, **186**: 59–74.

EPC. 1993. National earthquake support plan for British Columbia. Emergency Preparedness Canada, Ottawa, Ont.

FEMA. 1988. Typical costs for seismic rehabilitation of existing buildings. Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.

FEMA. 1989. Establishing programs and priorities for the seismic rehabilitation of buildings. Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.

FEMA. 1990. Estimated future earthquake losses for St. Louis city and county, Missouri. Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.

FEMA. 1992*a*. NEHRP handbook for the seismic evaluation of existing buildings. Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.

FEMA, 1992*b*. A benefit–cost model for the seismic rehabilitation of buildings. Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.

FEMA. 1992*c*. NEHRP handbook for seismic rehabilitation of existing buildings. Federal Emergency Management Agency, Building Seismic Safety Council, Washington, D.C.

Hasegawa, H.S., and Wetmiller, R.J. 1980. The Charlevoix earthquake of 19 August 1979 and its seismotectonic environment. Earthquake Notes, **51**(4): 23–37.

Hodgson, E.A. 1925. The St. Lawrence earthquake February 28, 1925. Bulletin of the Seismological Society of America, **15**(2): 84–105.

Hodgson, E.A. 1928. Tremblement de terre sur les rives du Saint-Laurent, le 28 février 1925 (analyse finale des données recueillies). Bulletin de la société géographique de Québec, **22**: 56–64.

Hodgson, E.A. 1936*a*. Preliminary report of the earthquake of November 1, 1935. Earthquake Notes, **7**(4): 1–4.

Hodgson, E.A. 1936*b*. The Timiskaming earthquake of November 1st, 1935. The location of the epicentre and determination of focal depth. Royal Astronomical Society of Canada Journal, **30**(4): 113–123.

Hodgson, E.A. 1945*a*. Industrial earthquake hazards in eastern Canada. Bulletin of the Seismological Society of America, **35**(4): 151–174.

Hodgson, E.A. 1945*b*. The Cornwall–Massena earthquake, September 5, 1944. Journal of the Royal Astronomical Society of Canada, **39**(1): 5–13.

Hodgson, E.A. 1950. The St. Lawrence earthquake, March 1, 1925. Publications of the Dominion Observatory, Ottawa, **7**(10): 361–436.

Hudon, P.-H. 1972. Rivière-Ouelle de la Bouteillerie, 3 siècles de vie, Comité du tricentenaire de Rivière-Ouelle.

IBC. 1993. Prepare now for an earthquake in British Columbia. Insurance Bureau of Canada, Vancouver, B.C.

ICBO. 1991. Uniform code for building conservation. International Conference of Building Officials, Whittier, Calif.

Knoll, F. 1983. Upgrading seismic resistance of buildings for moderate earthquake risk. Engineering Structures, **5**(2): 133–140.

Knoll, F. 1991. Seismic seminar series — Part IV. Montréal Structural Engineers, Montreal, Que.

Larochelle, F. 1982. Shawinigan d'autrefois. Imprimerie Paquet, Shawinigan, Que.

Legget, R.F. 1944. Earthquake damage at Cornwall, Ont. is extensive but of minor kind. Engineering News Record, pp. 318–319.

Look, D.W. 1991. The Seismic Retrofit of Historic Buildings Conference Workshop 1991. Western Chapter of Association for Preservation Technology, San Francisco, Calif. (28 papers, 8 appendices).

Mitchell, D., Tinawi, R., and Law, T. 1989. The 1988 Saguenay earthquake — a site visit report. Geological Survey of Canada, Ottawa, Ont., Open File Report No. 1976.

Mitchell, D., Tinawi, R., and Law, T. 1990. Damage caused by the November 25, 1988, Saguenay earthquake. Canadian Journal of Civil Engineering, **17**(3): 338–365.

Munro, P.S., and Weichert, D. 1989. The Saguenay earthquake of November 25, 1988 — strong motion data. Geological Survey of Canada, Ottawa, Ont., Open File Report No. 1976.

North, R.G., Wetmiller, R.J., Adams, J., Anglin, F.M., Hasegawa, H.S., Lamontagne, M., Du Berger, R., Seeber, L., and Armbruster, J. 1989. Preliminary results from the November 25, 1988, Saguenay Québec earthquake. Seismological Research Letters, **60**: 89–93.

NRC. 1992*a*. Guidelines for seismic evaluation of existing buildings. Institute for Research in Construction, National Research Council Canada, Ottawa, Ont.

NRC. 1992*b*. Manual for screening of buildings for seismic investigation. Institute for Research in Construction, National Research Council Canada, Ottawa, Ont.

PEP. 1992. British Columbia earthquake response plan. Provincial Emergency Program, Ministry of Attorney General, Province of British Columbia, Victoria, B.C.

Pernica, G., and Maurenbrecher, A.H.P. 1982. Survey of building damage in New Brunswick caused by the 1982 New Brunswick earthquake. *In* Preliminary report of the Miramichi, New Brunswick, Canada earthquake sequence of 1982. *Edited by* Anne E. Stevens. Earth Physics Branch, Ottawa, Ont., Open File Report 82-24.

Perry, C. 1990. Newcastle 27 December, 1989 (GMT) earthquake. Earthquake Engineering Research Institute Newsletter, **24**(5): 5–8.

Pierce, L. 1993. Risk and hazard analysis for British Columbia. Provincial Emergency Program, Ministry of Attorney General, Province of British Columbia, Victoria, B.C.

Pierre, J.-R. 1989. Comportement des postes et expertise des dommages causés par le tremblement de terre du 25 novembre 1988. Hydro-Québec, Montreal, Que., Internal Report. (Also available in English.)

Richter, C.F. 1958. Elementary seismology. W.H. Freeman and Company, San Francisco, Calif.

Smith, W.E.T. 1962. Earthquakes in eastern Canada and adjacent areas 1534–1927. Publications of the Dominion Observatory, Ottawa, **26**: 271–301.

Smith, W.E.T. 1966. Earthquakes in eastern Canada and adjacent areas 1928–1959. Publications of the Dominion Observatory, Ottawa, **32**: 87–121.

Stevens, A.E. 1980. Reexamination of some larger La Malbaie, Québec, earthquakes (1924–1978). Bulletin of the Seismological Society of America, **70**: 529–557.

Sweet, H.A. 1944. Cornwall, Ontario earthquake, September 5, 1944. Inspection Department of the Associated Factory Mutual Fire Insurance Companies, Boston, Mass., Internal Report, September 18, 1944.

USGS. 1976. A study of earthquake losses in the Salt Lake City, Utah area. U.S. Geological Survey, Denver, Colo., Open File Report 76-89.

Wetmiller, R.J. 1975. The Québec–Maine border earthquake of June 15, 1973. Canadian Journal of Earth Sciences, **12**: 1917–1928.

Wetmiller, R.J., Drysdale, J.A., Horner, R.B., and Lamontagne, M. 1989. Canadian earthquakes — 1985–1986. Geological Survey of Canada, Ottawa, Ont., Paper 88-14, Seismological Series No. 97.

Appendix A. Comments on the Charlevoix–Kamouraska seismic region

It has been conjectured by some engineers that earthquakes previously attributed to the Charlevoix–Kamouraska region actually had their epicentres near that of the 1988 Saguenay earthquake and that, consequently, another period of "seismic-dormancy" of 60 years would have started in 1988. This speculation, though appealing, is unsupported by the accumulated evidence. First, the 60-year cycle often alluded to by various nontechnical sources is totally fictitious, being simply an average interval between major earthquakes, including that of 1925; the actual recorded intervals vary anywhere from 10 to 100 years. Second, the 1925 Charlevoix–Kamouraska earthquake was recorded at practically all the seismograph stations in the world (Hodgson 1950); hence, the location of the 1925 earthquake is based on instrumental data.

Detailed calculations conducted by the Canadian seismologist Ernest A. Hodgson (1928, 1950) located the epicentre at 47.6°N, 70.1°W, i.e., under the St. Lawrence River between the towns of La Malbaie and Rivière-Ouelle, with an uncertainty of about ±40 km. Hodgson compared his instrumental location with descriptions of the effects of the main shock and with other reports about where aftershocks were felt, and concluded that this additional subjective evidence was compatible with the instrumentally determined epicentre.

More recently, using several different advanced analysis methods, other researchers have reexamined the instrumental data to more accurately relocate the 1925 epicentre. For example, Stevens (1980) has calculated it to be at 47.8°N, 69.8°W, with a ±15 km uncertainty, a result independently confirmed by Dewey and Gordon (1984). This would locate the epicentre near L'île aux Lièvres, approximately 30 km northeast from the location determined by Hodgson more than 50 years earlier. These studies conclusively demonstrate that the epicentre of one of the largest 20th century earthquake to occur in eastern North America is southeast of the Saguenay region by about 100 km, with estimated uncertainties and calculated statistical errors considerably less than 100 km.

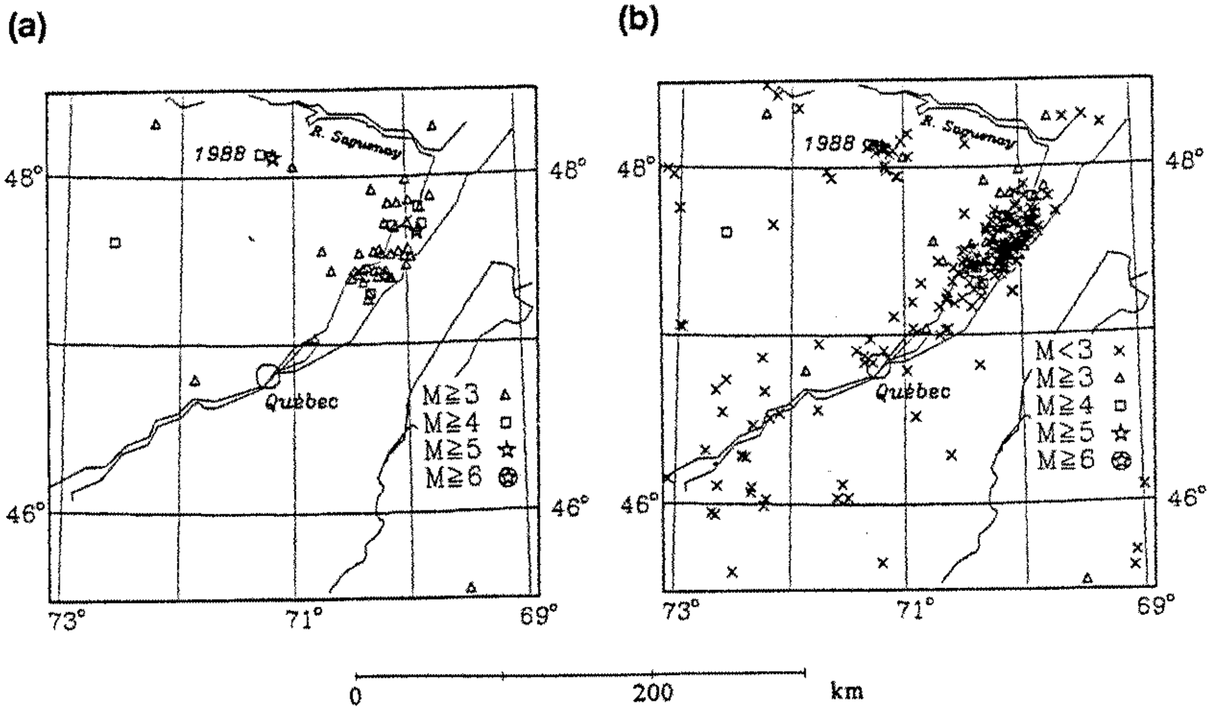

FIG. A1. Recent seismicity for the Québec region (1970–1990) for all earthquakes having a magnitude greater than (*a*) 3.0 and (*b*) 2.0 (Dr. A. Stevens, private communication, January 6, 1992, Geophysics Division, Geological Survey of Canada).

Finally, microseismicity (i.e., seismic activity only perceptible by highly sensitive instruments) is an important tool to understand and reveal local seismic activity. It is generally accepted that where numerous small earthquakes occur, less frequent earthquakes of large magnitude could also strike. Unfortunately, the opposite is not necessarily a guarantee of durable seismic inactivity. Aberrations, such as the 1988 Saguenay earthquake, are evidently always possible and consistent with some recent tectonic models (Basham 1987), which assume that a large earthquake can occur, albeit with a low probability, almost anywhere in eastern North America.

Figure A1*a* and A1*b* summarize recent seismic activity in a 100 000 km^2 region around the city of Québec for all recorded events exceeding magnitude 3.0 and 2.0 respectively, over the 1970–1990 period. Seismic activity in the Charlevoix–Kamouraska region is undeniable and has not decreased past November 1988. It is noteworthy that all visible seismic activity in the Saguenay region over that time period is attributable to the 1988 Saguenay earthquake and aftershocks. Apparently, based on modern tectonic models and respective microseismic activity of these regions, the seismic activity of the Charlevoix–Kamouraska region has not been affected by the 1988 Saguenay earthquake.

Therefore, and contrary to what has been erroneously alleged, since the last major earthquake in the Charlevoix–Kamouraska region occurred nearly 70 years ago, it appears that another such large seismic event in that region might be anticipated soon, maybe even before the end of this century, although the interval between major earthquakes in that region (or elsewhere) is quite variable and thus unpredictable. Current seismological models estimate that earthquakes up to magnitude 7.5 can be generated in this region (Basham et al. 1982).