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Les Terrasses de la Chaudière — Preliminary Risk Assessment of Existing Brick-faced Wall Panels

C. Banister, D. Cusson, M. A. Lacasse, A. Laouadi, B. Saassouh, K. Trischuk and J. Zhang

A1-008997-01
19 July, 2016

National Research Council Canada
Conseil national de recherches Canada
Canada

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Summary

Les Terrasses de la Chaudière (LTDLC) – Preliminary Risk Assessment of Existing Brick Walls

Les Terrasses de la Chaudière (LTDLC) complex was designed by Arcop Associates and built by the Campeau Corporation between 1976 and 1978. The complex is composed of four towers (3 government offices and one hotel) located in downtown Gatineau, between Promenade du Portage, Eddy, Wellington and Montcalm streets. The three government office towers are 7, 19 and 28 stories high and are linked at their first and second levels by a retail concourse and the basement levels by a tunnel system. It is the single largest federal office complex in Canada with a total rentable floor area of 142,353 m², and accommodates over 6,000 people. The complex contains the administrative headquarters of Environment and Climate Change Canada, Aboriginal Affairs and Northern Development Canada, Canadian Heritage, the Canadian Radio and Telecommunications Commission, and the Canadian Transportation Agency.

The three government office towers (Blocks 100, 200 and 300) are reinforced concrete structures, covered with prefabricated, brick-faced panels that form most of the building envelope. Above the second floor, the exterior walls consist of brick-veneer over a concrete back-up wall with aluminum-framed windows and doors. The exterior wall was designed as a drained system, using the airspace between the brick and insulated back-up wall as the drainage cavity. The exterior envelope of the lower two building levels forming the pedestrian concourse is of conventional masonry, rather than prefabricated systems.

Since the construction of the complex, the exterior brick-cladding has undergone advanced deterioration, presently creating potentially serious safety issues. In the late 1990's, the brick cladding of the LTDLC towers was a concern because of premature deterioration and serious safety issues related to the risk of falling bricks. Upon the first report of brick falling in 1997, there have been numerous studies of the brick cladding and the extent of deterioration of the walls. These studies have resulted in recommendations for a program to manage the risks with regular inspection and repair, and use of overhead protection measures around the site.

Current status

A permanent solution to address the above health and safety risks for Blocks 100, 200 and 300 is currently being developed through the design of a new building envelope, with construction expected to start in 2018 and end in 2023. It is anticipated that the exterior building envelope will be implemented in at least two phases, such that the envelopes of the exterior towers will first be rehabilitated and thereafter, the lower two levels which use a different cladding type. Public Services and Procurement Canada (PSPC) is engaging a consultant to develop schematic designs and construction implementation strategies to rehabilitate the LTDLC complex building envelope that will address these health and safety issues. Whereas in the short to medium term, the existing wall panels are experiencing accelerated deterioration with a growing risk of brick falling onto public areas at the base of the towers, consideration ought to be given to ensuring that as broad an area at the base and perimeter of the buildings of the LTDLC complex be fully protected by the installed overhead protection measures.

The National Research Council Canada (NRC) has been retained by PSPC to conduct a preliminary risk assessment study of the existing brick wall panels. The objectives are to review the existing inspection reports, to provide risk assessment of observed deterioration of the brick walls, and to make

recommendations on alternative facade maintenance options with related costing. NRC has been asked to provide technical support to PSPC on the following tasks:

1. Technical review of prior reports and data sets provided by PSPC related to the condition of the brick-faced wall panels.
2. Overall risk assessment of observed deterioration of brick wall panels.
3. Provide alternative facade maintenance-preservation options with related costing.

Key considerations

Despite the detailed observations of brick failures in previous inspections, the underlying causes of the premature deterioration of the brick walls had not been investigated. This step is required for a clear understanding of the pathology in order to make a sound assessment of the deterioration rates and risks, and to propose cost-effective facade maintenance solutions to PSPC.

Several potential causes of deterioration have been and will continue to be investigated by NRC; they include: (i) differences in thermal expansion rates between bricks, epoxy mortar and steel bars creating stresses and cracking of the bricks and joints due to annual and daily temperature variations; (ii) corrosion of steel bars creating internal pressure and cracking of the surrounding bricks; (iii) moisture absorption and freeze-thaw resistance of bricks resulting in cracking; (iv) stiffness of bricks and mortar which makes them brittle and subject to movement-induced cracking; and, (v) bowing of concrete panels due to differential drying shrinkage of the concrete.

Preliminary results suggest that the primary cause of failure is the differences in thermal expansion rates amongst brick units, epoxy mortar and the steel reinforcing bars. The selection of a high-strength self-leveling mortar to provide for a reinforced brick fascia affixed to the concrete panel has caused wide-spread failure of brick units, the failure being evident from observations described in the several of the reports and from on-site inspection. As such, is this façade system nonetheless serviceable?

The brick veneer wall panel system will require continuous monitoring and perhaps repair for the remainder of its service life; it may indeed have already reached its end of life. As such it will continue to be a burden on PSPC resources whilst not providing the level of performance as was originally intended in its design. The courtyard will not yet be accessible, the overhead protection will still be required and risks to injury will nonetheless be present until such time as the brick panel wall assembly is replaced.

Recommendations

The recommendations provided below are based on an initial assessment of the bricked-faced wall panels as described in the report; these are to be updated in the subsequent and Final report to PSPC:

- Undertaking inspections of brick wall panels at least on an annual basis;
- Estimating, on the basis of inspection results (currently being collected):
  - Rate of deterioration & remaining life of brick façade
  - Risks and change in risk associated with changes in rate of deterioration
  - Cost of repair or other interventions
- Determining the extent of repair, or other interventions, required to maintain reliability (level of acceptable risk) of the brick façade.
- Repairing the envelope air barrier if found defective

Additional details in respect to the findings and recommendations are to be found in this report.

High Performance Roofing and Walls Technologies

Les Terrasses de la Chaudière — Preliminary Risk Assessment of Existing Brick-faced Wall Panels

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A Report for

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Major Crown Projects / Real Property Branch
Promenade du portage, Basement, Room 8
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19 July, 2016

Les Terrasses de la Chaudière — Preliminary Risk Assessment of Existing Brick-faced Wall Panels

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B. Saassouh, K. Trischuk and J. Zhang

1. Introduction

1.1 Background

Les Terrasses de la Chaudière (LTDLC) complex was designed by Arcop Associates and built by the Campeau Corporation between 1976 and 1978. The complex is composed of four towers (3 government offices and one hotel) located in downtown Gatineau, between Promenade du Portage, Eddy, Wellington and Montcalm streets (see Figure 1). On the West side, the complex is bordered by Delta Hotel, but the hotel and its parking garage are excluded from this project. The three government office towers are 7, 19 and 28 stories high and are linked at their first and second levels by a retail concourse and the basement levels by a tunnel system. The total rentable floor area is 142,353 m^2, accommodating over 6,000 people, as well as retail and storage space. It is the single largest federal office complex in Canada, containing the administrative headquarters of Environment and Climate Change Canada, Aboriginal Affairs and Northern Development Canada, Canadian Heritage, the Canadian Radio and Telecommunications Commission, and the Canadian Transportation Agency.

The three government office towers are reinforced concrete structures, covered with prefabricated, brick-faced panels that form most of the building envelope. Above the second floor level, the exterior walls consist of brick-veneer over a concrete back-up wall with aluminum-framed windows and doors. The corner (bay) sections are comprised of a curtain-wall assembly, with insulated clad spandrel panels. The exterior wall was designed as a drained system, using the airspace between the brick and insulated back-up wall as the drainage cavity. The exterior envelope of the lower two levels forming the pedestrian concourse is of conventional masonry, rather than prefabricated systems.

Over the years of service, deterioration of the exterior brick-cladding has steadily progressed, attaining by the late 1990s, a more advanced stage of deterioration and since that time, creating potentially serious public safety issues that Public Services and Procurement Canada (PSPC) have been actively attempting to manage over these years.

A brick inspection and repair program is underway to maintain safety standards, but a permanent solution is also envisaged whereby the entire building envelope system, including windows, curtain wall, the mechanical and electrical interface, and interior finishes is to be rehabilitated. It is anticipated that the replacement of the exterior building envelope will be implemented in at least two phases, so that the tower exterior envelopes will first be rehabilitated, followed by rehabilitation of the lower two levels forming the podium and the ground level circulation systems.

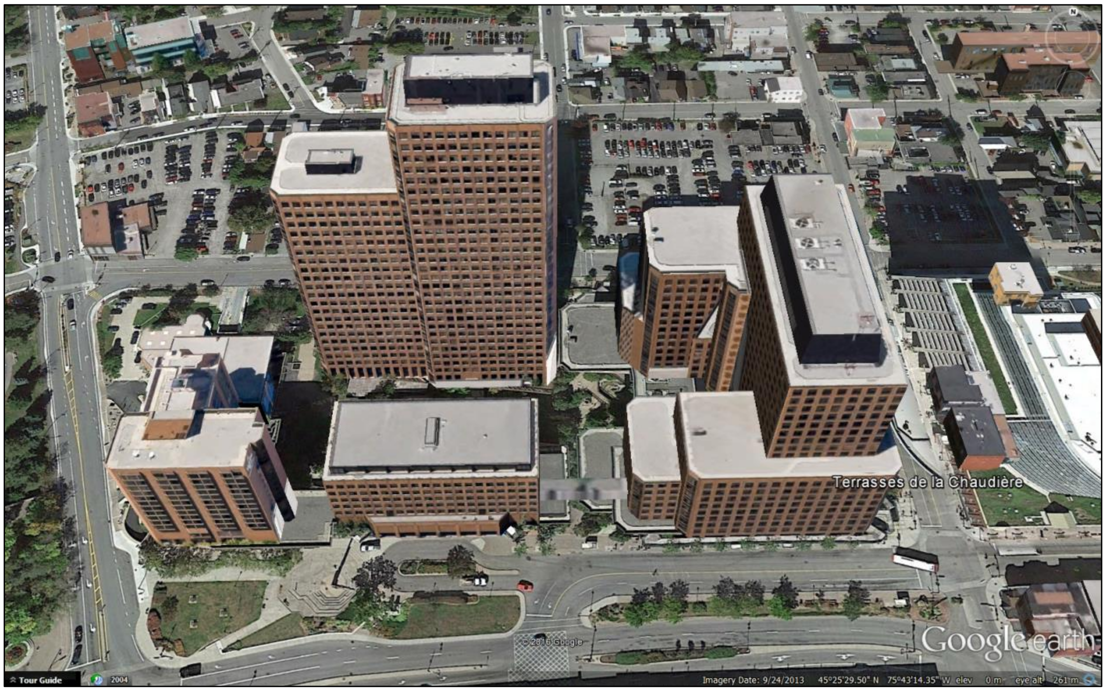

Figure 1: Les Terrasses de la Chaudière Complex, showing Block 100 (right), Block 200 (centre back), Block 300 (centre front), and the hotel (left, not part of project). (Picture from Google Earth)

PSPC is engaging a consultant to develop schematic designs (incl. seismic upgrades) and construction implementation strategies to rehabilitate the LTDLC complex building envelope to address safety issues, as described in the Building Envelope Retrofit Feasibility Study (Smith Carter 2013).

The work of the consultant will entail a detailed review of all available documentation and reports; analysis of the as-built conditions; review of the options for the exterior building envelope and seismic resistance; development of four design options as well as a recommended option; construction implementation strategy, and presentations to authorities with jurisdiction.

1.2 Objectives

The National Research Council Canada (NRC) has been retained by PSPC to conduct a preliminary risk assessment study of the existing brick wall panels. The objectives are to review the existing inspection reports, to provide risk assessment of observed deterioration of the brick walls, and to make recommendations on alternative facade maintenance options with related costing. NRC has been asked to provide technical support to PSPC on the following tasks (focusing on Blocks 100, 200 and 300):

(1) Technical review of reports and data sets provided by PSPC related to the condition of the brick-faced wall panels.
(2) Overall risk assessment of observed deterioration of brick wall panels.
(3) Provide alternative facade maintenance-preservation options with related costing.

Accordingly, each of these tasks forms the basis for the work plan and each is dealt with in turn, the results of which have been provided in their respective sections.

2. Technical review of documentation & inspection of wall panels (Task 1a[1])

The intent of the technical review of documentation and available data sets was to:

(1) Collect all pertinent documentation and data that were made available to NRC, to permit commentary of the pathology of deterioration and from which to inform the risk assessment of the different LTDLC buildings and facades that is described in Task 2 (Chapter 5);
(2) Identify areas where missing data and clarifications are required from PSPC or their consultant and that could further inform on the expected life of the brick masonry facades;
(3) Inform at what locations on a building should inspections should be conducted, and as well, which buildings should be inspected to gain further knowledge and understanding of the pathology of deterioration of the brick masonry wall panels;
(4) Provide a basis for proposing brick inspection and repair options as may be described in Task 3 (Chapter 6).

A review of proposed options for brick inspection and repair of the brick masonry panels is provided in Task 3 whereas results of on-site and in-situ inspection of wall panels are not yet available as inspections have not yet taken place. The results of in-laboratory inspection of a wall panel specimen and results of laboratory testing of wall components are provided in Chapter 4.

2.1 Overview of previous condition assessment studies and repairs

The first sign of a potential issue with the brick cladding on the LTDLC buildings arose in December 1995 at which time a complaint was made regarding pieces of bricks that landed into the outdoor play area of the daycare facility located at the base of Block 200 at the South elevation. Two other observations of fallen bricks into the playground area were also reported in March 1996 and September 1997. Following the first observation, several investigations and remedial work have since been conducted and are summarized below:

- **March 1997** – CABA (Consultants André Beaulieu & Associés) completed a study of the exterior walls of Block 300, including thermographic analysis, visual inspection, and structural analysis of wall panels. They observed bowing and cracks in some wall panels, a few damaged bricks (splitting), and heat loss problems between the wall panels. They concluded that panel anchors were sound, cracks in brick cladding were the result of freeze/thaw cycles, but that overall, the building was in "excellent condition".
- **December 1997** – Larivière Construction completed an emergency inspection and replacement of loose bricks on Blocks 100, 200 and 300. (Report missing)[2]
- **March 1998 –** CABA and AAR (Adjeleian Allen Rubeli) jointly conducted a building envelope and structural evaluation of Blocks 100, 200 and 300. (Report missing)
- **October 1999** – JCAL (John Cooke & Associates Ltd) performed a free fall brick trajectory testing at Blocks 100 and 200, and indicated that the impact of falling bricks can cause serious injury as bricks can break into numerous small projectiles on impact with a hard surface. They concluded however that the risk of falling bricks drifting beyond 1200 mm from the face of the building was very unlikely.

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[1] Relates to tasks described in the Project Proposal; Proposal provided in Appendix A

[2] Report missing – this description indicates that reference to this report have been made in one of the reports received from PSPC but it was not part of the set of reports that were provided to NRC.

- **October 1999 –** CABA completed study and repair of South and partial West wall of Block 200, including structural and thermal study of building, inspection of brick walls with sounding, replacement of loose bricks, and repair of cracks, joints, ventilation and drainage. CABA concluded that the observed deterioration was related to exterior elements and that poor drainage and ventilation of the cavity behind the bricks were the primary causes of brick damage[3]. Furthermore, CABA concluded that inaction will result in continued and increased brick deterioration.
- **December 1999** – CABA conducted a water infiltration study on Blocks 100, 200 & 300. (Report missing)
- **September 2000** – JCAL performed an inspection of all brick panels on Blocks 100 and 200, plus part of Block 300, and observed 1214 cracked bricks generally located at the edge of panels and at window edges. JCAL judged that the deterioration was likely related to reinforcing bars present at the same locations and that most of the defects encountered can be considered normal defects expected in the life of a building. They also concluded that corroding of the reinforcing bars was caused by, and not causing, cracks in brick. Cracks in bricks were deemed to result from thermal expansion and contraction of the bricks. JCAL recommended considerable repair work and regular brick inspections (every 3 to 5 years) to ensure bricks will not deteriorate to a point that pieces would fall off the building. The identified damaged bricks were actually repaired in 2001 and 2002.
- **April 2001** – Morrison Hershfield conducted a second opinion review of previous CABA investigations. They concluded from CABA observations that the isolated cracking of bricks was due to corrosion of the reinforcing bars. They recommended wall repair and maintenance, but not a complete rebuild unless deterioration increased substantially. Morrison Hershfield also concluded that precipitation was the probable source of water to saturate the bricks on the buildings.
- **September 2003** – JCAL completed an inspection of all brick walls on Blocks 100, 200 and 300 and observed 1672 cracked brick generally at the edge of panels or at window edges, noting for the first time that pieces would have fallen by themselves within the next two years. JCAL indicated that East elevations exhibit most deterioration and judged that it was indicative of extreme temperature changes causing greater amount of cracking due to differential thermal expansion of brick and reinforcing bars. JCAL recommended essential repair work and periodic inspection (every 3 years) to ensure that broken bricks are identified and replaced. Partial repair of the 1672 damaged bricks was conducted between 2003 and 2006 (some elevations of Block 200 were excluded).
- **March 2005** – According to PTVD 2015 (Patenaude Trempe Van Dalen), PSPC performed a thermographic study of the complex and concluded that there were no significant air leakage anomalies. (Report missing)
- **November 2009** – JCAL completed an inspection of all brick walls on Blocks 100, 200 and 300 and observed 7883 cracked bricks generally at panel edges or at window edges (89% of total cracked bricks), noting for the first time pieces that would have been at risk of falling within one year. JCAL noted that the count included bricks first identified in their 2003 inspection that were still not replaced. JCAL indicated that East and South elevations exhibited the most deterioration. They also commented that the South elevation of Block 200 exhibited surprisingly little deterioration where flashings had been installed in the vertical panel joints (as directed by CABA in 1997), which prevented water from getting to the sides of the brick panels.
- JCAL also observed a brick dropping during their work on Block 200, deflecting off a window sill and landing approximately 30 meters from the building, and concluded that the risk of falling bricks causing injury is high and danger around the base of the building is large. JCAL noted that the life expectancy of their recommended brick repair is 10 years. Furthermore, JCAL concluded for the first time that steel

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[3] In this report "brick damage" refers to bricks that were observed to have cracks or were loose.

reinforcing corrosion was causing bricks to crack. The repair of all 7883 identified damaged bricks was done in 2011 and 2012.

- **November 2010** – JCAL and RMA (Robertson Martin Architects) jointly conducted a visual inspection of some panel anchors at Blocks 100 and 200. They concluded that the gravity and lateral connections of the typical single-window and double-window panels were adequate for the gravity and seismic forces of the National Building Code (NBC 2005), with reserve capacities of 13% and 21% for each type of panel, respectively. They also indicated that, in a potential future re-cladding project, the option of adding a new veneer on top of the existing bricks is not recommended due to the limited reserve capacity of the existing anchors.
- **September 2012** – JCAL conducted an inspection at Block 200 and observed cracking parallel to brick face, which could permit large sections of brick faces to fall altogether. Similar observations had been made on lower levels and the conditions had been attributed to uncontrolled air leakage through holes left in precast panels for access equipment anchors used for the 1997/1998 repairs. 2012 observations included saturated bricks, but the source of moisture was not investigated. In addition, the air space in the wall assembly was found to be filled with saturated, expanded polystyrene insulation where split bricks were removed and replaced. The extent of this condition is not known. JCAL stressed that cracking in bricks parallel to brick face creates different and higher risk than fragments resulting from cracking perpendicular to brick face. JCAL pointed out a new risk that multiple brick faces would fracture into multiple smaller fragments on impact with overhead protection, with fragments following unpredictable trajectory that could extend beyond overhead projection. JCAL also warned that brick fragments, or groups of brick faces, hitting window sills will likely be deflected and could hit pedestrians or vehicles beyond the overhead protection.
- **September 2014** – Adjeleian Allen Rubeli (AAR) completed an impact study for overhead protection around the base of the buildings. AAR repeated the risk of individual or small groups of brick faces dislodging completely and falling without warning, resulting in significant hazard to pedestrians in the vicinity of the building. AAR provided their caution of the risk of fragments of brick bouncing off the overhead protection.
- **September 2014** – JCAL completed an inspection of all brick walls on Blocks 100, 200 and 300 and observed 3223 cracked brick generally at panel edges and at window edges (87% of total cracked bricks), noting pieces that would have been at risk of falling within one year. JCAL indicated that East and South elevations continue to exhibit the most deterioration and again commented that the South elevation of Block 200 exhibited less deterioration where flashing was installed within the panel joints, preventing water from getting to the sides of the brick panels. JCAL repeated their previous comment that falling bricks could deflect off window sills and land in the order of 30 meters from the building, reiterating that the risk of falling bricks causing injury is high and danger around the building is large. JCAL noted that the life expectancy of their recommended brick repair is 5 years.
- **January 2015** – Patenaude Trempe Van Dalen (PTVD) completed a review of the previous brick wall panel investigations from 1997 to 2014. The following is an excerpt from PTVD's report summarizing their review *"When deterioration of the brick was first investigated, CABA provided the opinion that a comprehensive and costly repair program was required, although the root cause of the deterioration had not actually been identified. When JCAL first investigated the condition of the brick cladding, they provided an opinion that a much less extensive program of repair would be effective in maintaining the brick cladding and PWGSC opted to adopt the JCAL approach. JCAL did not undertake a detailed study of the cause of the deterioration and described it as expected in the life of a building. As the result of four complete surveys and other detailed investigations of specific areas of concern over fourteen years, JCAL assessed that there is an on-going, rapid deterioration of the brick that warrants regular inspection and repair to remove the hazard of brick falling from the walls, as well as permanent overhead protection around the base of the buildings. More importantly, JCAL have determined that the type of deterioration and risk has evolved and now includes the risk of larger groups of brick falling. They have concluded that this inspection and repair program can only extend the service life of the brick for another 5 years, but have cautioned that even through that timeframe there are risks that are not appropriately handled by the installed protection.*

> *Upon review of the documentation provided, PTVD concurs with the risk assessments of JCAL and AAR, although we are not in full agreement with JCAL on the rate of deterioration. Nonetheless, there is a clear need for an on-going risk management program and we have identified some shortcomings of the current program. Specifically, we note that the inspection and repair program has been strictly reactive to-date, and the repairs have lagged too far behind the inspection. Furthermore, we note that the installed protection does not extend into areas that are highly likely to be landing locations for falling brick that deflects off the building wall or rebounds off the overhead protection. We have suggested that the risk management program could be adapted to expedite the repairs following an inspection, to include proactive measures to slow the deterioration and to provide superior protection to pedestrians and vehicles at the base of the faces along the streets on the outer perimeter of the site. We believe that the adapted program would minimize risks to building occupants and the public around the site, while affording PWGSC more time to plan the inevitable replacement of exterior cladding on the buildings."*

2.2 NRC comments on previous reporting on brick damage inspection

Upon the first report of brick falling in 1997, there have been numerous studies of the brick cladding and the extent of deterioration, as summarized above. These studies have resulted in recommendations for a program to manage the risks with regular inspection and repair, and use of overhead protection measures around the site. Table 1 presents a listing of the condition assessment studies and repair work related to the brick wall deterioration issue (structural evaluations of buildings not included).

Despite the many inspections that have been conducted between 1997 and 2015, little gain has been made in the understanding of the underlying causes of the observed deterioration and the determination of the deterioration rate. The following discussion will focus on the brick damage aspect of these studies and the gaps noted.

From Table 1,**Error! Reference source not found.** the following issues can be identified:

- Some inspection reports (or part of) were not available for review
- No studies have focused on identifying the root causes of the observed deterioration
- Inspections have been conducted at varying time intervals (may be related to contracting issues)
- Inspections have been done by different contractors (CABA at first, then JCAL later on), thus using different approaches
- Some repairs have been completed several years after the inspection (may be related to contracting and budget issues)
- Different levels of scrutiny were used between contractors (e.g. qualitative vs. quantitative observations)
- Different levels of scrutiny were used between inspections of same contractor (e.g. hairline cracks reported (JCAL 2010) vs. not reported (JCAL 2015)
- Different ways of reporting observed damage from same contractor (e.g. total number of cracks for all buildings together, vs. % panels with damaged bricks per elevation with no indication of number of bricks per panel, vs. detailed numbering of bricks per elevation)

Of all sets of data collected from the studies listed in Table 1**Error! Reference source not found.**, two rovide detailed information on the number of damaged bricks per building elevation. They are identified in Table 2**Error! Reference source not found.** for each elevation of each building, as reported by JCAL (2015-1). As observed by JCAL, the number of damaged bricks was higher on East and South building facades compared to the West and North facades, indicating that some of the inherent damage mechanisms depend on the extent of daily temperature changes being the largest, in general,

Table 1 – List of Reports on Condition Assessment of LTDLC brick wall cladding

Work Date (yyyy-mm)	Report Author & Date	Building Elevation	Scope of work	Data status	Brick damage data type
1997-03	CABA (1997-04)	Block 300	-Thermographic analysis -Visual inspection -Structural and wall panel analysis	Received[4]	Qualitative observations of panel cracks and brick splitting (no numbers given)
1997-12	Larivière Construction	All blocks	-Emergency inspection -Replacement of loose bricks	missing report	
1998-03	CABA & AAR	All blocks	-Building envelope and structural evaluation	missing report	
1999-10	JCAL/JWE (1999-10)	Blocks 100/200	-Free-fall brick trajectory testing	Received	
1999-10	CABA (1999-11)	Block 200, South	-Structural and thermal study -Inspection of brick walls with sounding -Replacement of loose bricks -Repair of cracks, joints, ventilation, drainage	missing Appendix 4	
1999-12	CABA	All blocks	-Water infiltration study	missing report	
2000-03 / 2000-09	JCAL (2000-12)	All blocks	-Inspection of brick walls -Removal of loose bricks	Incomplete - missing Appendix C	-Total number of damaged bricks -% of panels with damaged bricks reported for each elevation
2001-04	Morrison Hershfield (2001-04)	Blocks 100/200	-Review of previous work (excluding JCAL 2000-12 report)	No new data	
2003-06 / 2003-09	JCAL (2004-03)	All blocks	-Inspection of brick walls and joints -Removal of loose bricks	Incomplete - Elevation drawings	-Total number of damaged bricks -Qualitative observations of damaged bricks (no numbers given)
2004, spring-fall	JCAL (2005-06)	Block 200, East	-Inspection of brick walls	Received	Qualitative observations of panel cracks and brick splitting (no numbers given)
2005-03	PSPC	All blocks	-Thermographic study	missing report	
2009-04 / 2009-11	JCAL (2010-02)	All blocks	-Inspection of brick walls -Removal of loose bricks -Recommendations for immediate repairs	incomplete - missing Elevation drawings	Number of damaged bricks reported for each elevation
2010-11	RMA/JCAL (2011-02)	Blocks 100/200	-Visual inspection of panel anchors (partial)	Received	
2012-09	JCAL (2012-10)	Block 200	-Review of dismantled panel (NE corner, F21)	Received	
2013-11 / 2014-09	JCAL (2015-01)	All blocks	-Inspection of brick walls -Removal of loose bricks	Received	Number of damaged bricks reported for each elevation
2014-09	AAR (2014-09)	All blocks	-Impact study	Received	
2015-01	PTVD (2015-01)	All blocks	-Review of previous work -Review of PSPC's risk management program	No new data	

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[4] "Received" refers to reports obtained from PSPC; "missing" reports requested but not received, or portions of report missing; "incomplete" reports: received but some information missing; "No new data" reports: received and provides a review of previous work

Table 2 – Number of damaged bricks reported by building elevations and time

Building elevation	JCAL (2010-02)	JCAL (2015-01)
Block 100 - East	1076	598
Block 100 - South	1548	457
Block 100 - West	654	420
Block 100 - North	530	384
Block 100 - Total	**3808**	**1859**
Block 200 - East	1268	281
Block 200 - South	917	326
Block 200 - West	728	271
Block 200 - North	746	249
Block 200 - Total	**3659**	**1127**
Block 300 - East	170	28
Block 300 - South	280	112
Block 300 - West	56	29
Block 300 - North	45	68
Block 300 - Total	**551**	**237**
All blocks - East	2514	907
All blocks - South	2745	895
All blocks - West	1438	720
All blocks - North	1321	701
All blocks - Total	**8018**	**3223**

on the East and South facades. One interesting observation that has not been reported earlier is the clear reduction of this adverse effect from 2010 to 2015. For example, the ratio of damaged bricks between East/South and West/North facades is 1.9 in 2010 and only 1.3 in 2015. This may indicate that the earlier mechanisms of deterioration were more affected by temperature changes compared to the current (perhaps transformed) mechanisms. However, from these limited data (i.e. 2 points in time, and not being sure of the underlying mechanisms), it is rather difficult to determine the rate of brick deterioration or whether it is increasing linearly or exponentially.

An attempt, however, has been made by PTVD (2015) to assess the rate of brick deterioration by looking at the overall number of damage bricks (all buildings together) from 4 different inspections conducted by JCAL in 2000, 2003, 2009 and 2014. The rates are expressed in terms of number of bricks per month, as the time elapsed during two consecutive inspections (Table 3). As commented by PTVD (2015), the rate of deterioration from 2000 to 2015 is certainly not exponential but rather increasing at least linearly given the variation in the data that can be expected for this type of work; this review did not consider any repairs that may have been previously made. Nonetheless, the sudden reduction in the rate of brick deterioration from 2010 to 2015 is left somewhat unexplained.

Interestingly, if one averages the rate of damage to bricks over the first 20 years from when the complex was constructed, it appears that the rate is at least an order of magnitude less than the damage rate from 2000 onwards. This suggests that from the onset of observable damage just prior to 2000, the useful life of the façade may indeed have been attained.

Table 3 – Number of damaged bricks over time (all buildings together)

Inspection time	Reported by JCAL (2015-01)	Re-assessed by PTVD (2015-01)
2000	1214 bricks	4.5 bricks/month[5]
2003	1672 bricks	45 bricks/month
2009	7883 bricks	106 bricks/month
2014	3223 bricks	56 bricks/month

As concluded by PTVD (2015), it is found that the available data remain insufficient to make a proper determination of the rate of brick deterioration (even when data are grouped from all buildings together). This is partly explained by the following reasons:

- Too few data points available over time (even fewer when considering building elevations);
- Inconsistencies in counting methodology
    - Counting errors (i.e. unrepaired bricks observed in 2003 identified as new damage in 2009);
    - Repaired bricks not included in the observations;
    - Inspection periods spanning many months;
- Changes made to the building envelope
    - Replacement of some wall panels on Block 200 (South elevation), thus having a new service life;
    - Reduced scope of repair work (e.g. damaged bricks repaired or replaced in the early years vs. loose bricks removed in the later years);
    - Application of moisture control strategies to some wall panels (e.g. vertical flashing installed on the South elevation of Block 200).

Analysis of damaged brick units by Block, floor level and façade direction — Since it is possible that brick damage be related to the height or the floor level of the buildings (e.g. higher wind, stronger driving rain, more sun exposure), the data provided by JCAL during their last 2015 inspection were re-analysed with the number of damaged bricks counted for each floor of each building elevation. Also, the type of damaged bricks was also considered in the analysis (e.g. Type X being a normal brick, Type Y being a row lock brick, and Type Z being a soldier brick).

Figure 2 to Figure 4 represent the number of damaged bricks for each elevation of Blocks 100, 200, and 300, respectively (all brick types together). It is noted that damage to the conventional masonry walls below the 2nd floor level was ignored, since it is outside the scope of this project. It is also noted that the data for the uppermost level of each building represent the damage of the parapet sections only, which is different from a conventional brick wall panel with window opening(s). Before commenting on the rate of observed damage, the data still need to be normalized by the number of single panels (or equivalent) at each floor level, since the lower storeys of Blocks 100 and 200 have a larger number of panels as compared to the fewer panels at higher floor levels. Figure 5 to Figure 7 illustrate the number of damaged bricks per single panel or equivalent (e.g. double panels at Block 200 counted as two single panels) for each elevation of Blocks 100, 200, and 300, respectively.

With reference to Block 100, the total number of damaged bricks per floor level appears to be relatively independent of building height from Floor 3 to Floor 19. Despite some local high peaks (e.g. Floor 6 East,

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[5] Number of reported damaged bricks in 2000; 20 months since completion of TDLC; average of 4.5 bricks/month

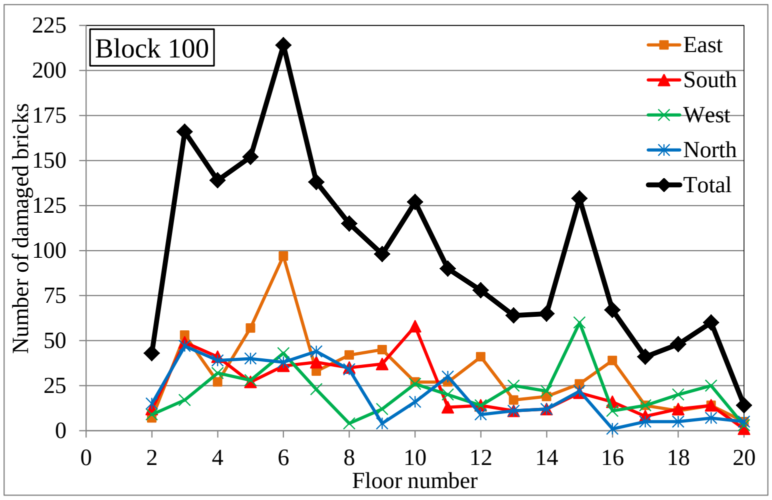

Figure 2 – Number of damaged bricks per floor level – Block 100 (as of 2015)

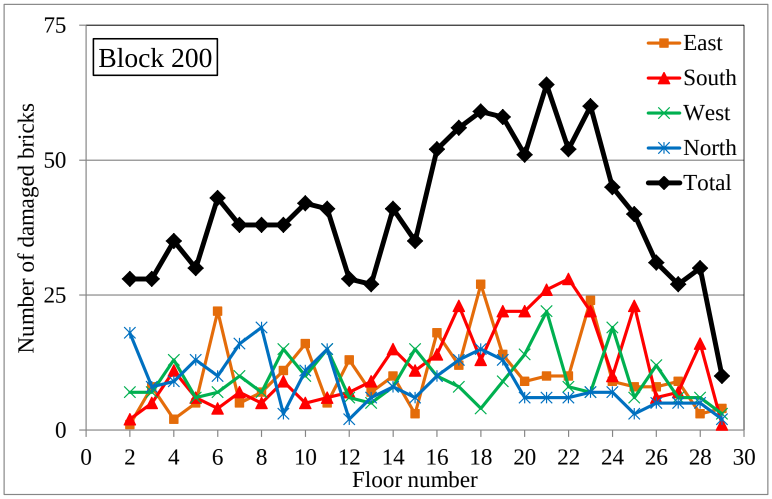

Figure 3 – Number of damaged bricks per floor level – Block 200 (as of 2015)

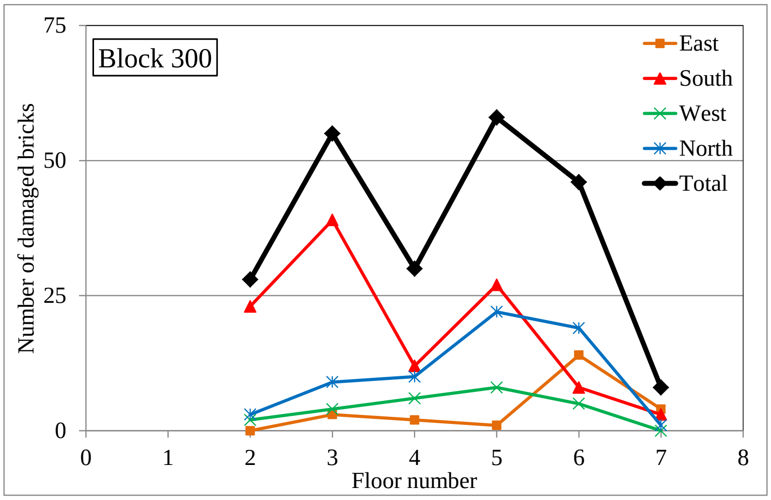

Figure 4 – Number of damaged bricks per floor level – Block 300 (as of 2015)

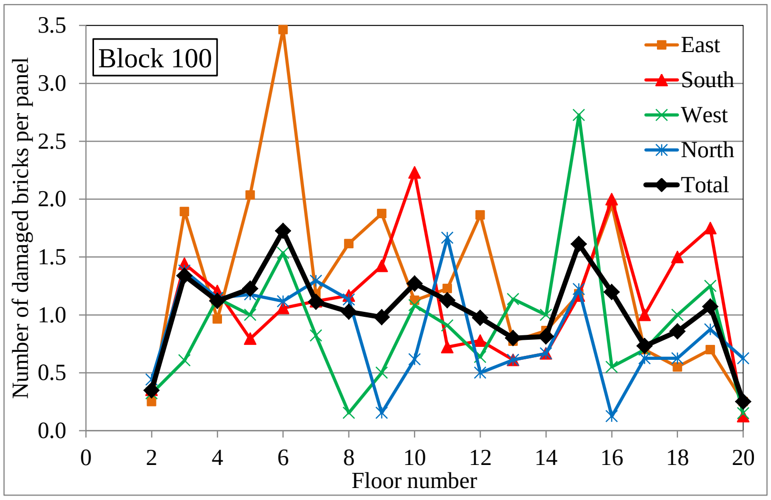

Figure 5 – Block 100(as of 2015) Normalised number of damaged bricks/panel at Floor number

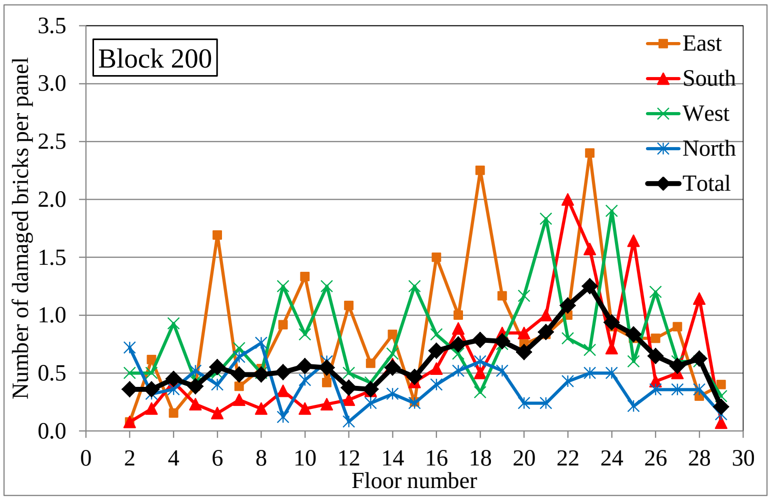

Figure 6 – Block 200 (as of 2015) Normalised number of damaged bricks/panel at Floor number

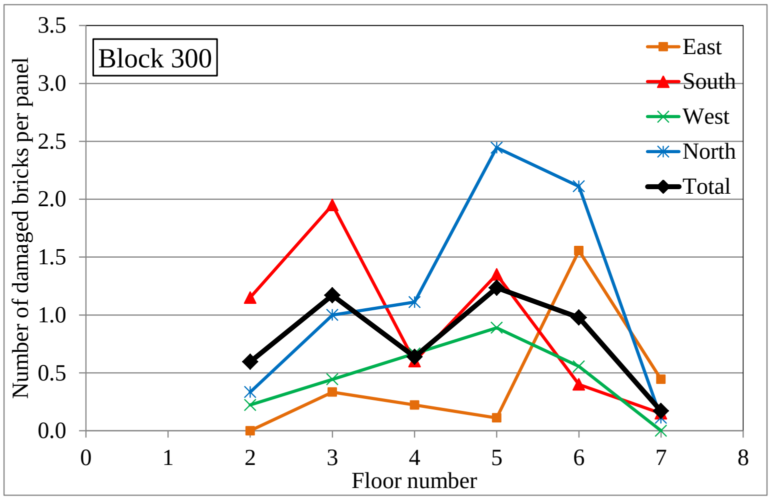

Figure 7 – Block 300 (as of 2015) Normalised number of damaged bricks/panel at Floor number

Floor 15 West), the rate of damage seems to be slightly higher on the East and South elevations than on the West and North elevation, as reported earlier. With a total number of 1860 single panels, Block 100 has an average number of 1.0 damaged brick per panel.

Regarding Block 200, the total number of bricks per floor level increases steadily from Floor 3 up to Floor 23 and then sharply decreases from Floor 23 to Floor 29. It is noted that Floor 23 corresponds to the level separating the lowest towers from the highest tower, which may indicate that the top portion of the higher tower is in relatively better shape than the lowest portions of Block 200. At the lower floors (up to Level 15), the East and West elevations seem to have higher rate of damage, while at the higher floors (Level 16 and up), only the North elevation remains with a relatively low rate of damaged bricks. With a total number of 1980 single panels (or equivalent), Block 200 has an average number of 0.6 damaged brick per panel.

As regards Block 300, the total number of bricks per floor level appears to be relatively independent of the floor level. In the lower floors (up to Level 4), the South elevation has the highest rate of brick damage, whereas the trend reverses for the upper floors (Level 5 and up) where the North elevation clearly has the highest rate of damage. This observation is not typical and may indicate that the damage on the North elevation of Block 300 may be caused by a damage mechanism that is somewhat less dependent on daily temperature differences. On the other hand the total number of damaged bricks on the West side of Block 300 is quite small – 30 bricks for all floor levels (7 levels), which in fact is a small number compared to the other buildings of the complex. Hence for Block 300, it only requires a few additional or fewer damaged bricks of a given type to affect changes to the normalised values at a given floor level; as the absolute number of bricks damaged remains small. With a total number of 329 single panels, Block 300 has an average number of 0.7 damaged brick per panel. This in fact confirms that the extent of damage for Block 300 is quite comparable to panels of the other blocks when normalizing the number of damaged bricks by the number of panels.

Analysis of damage by type of brick unit — The type of damaged bricks was also investigated, since certain damage mechanisms may affect one type of brick more than others. For example, Types Y and Z bricks, being rowlock and soldier bricks respectively, all have steel reinforcing bars going through their core openings, whereas only a small fraction of Type X bricks have embedded steel bars. It was thought that if the fraction of Type Y or Type Z bricks that were damaged was greater than the fraction of damaged Type X bricks, rebar corrosion might be the prime cause of deterioration for these brick types.

The results shown in Table 4 are the proportion, per panel, of damaged brick of a given type to that of all damaged bricks of the same type. The ratios are arranged in columns by building block (i.e. Blocks 100, 200, 300) and for each block by façade direction (E, S, W, N). The average number of damaged bricks of a given type per panel is also provided as a measure against which to compare the respective values of the proportion of damaged brick units according to Block and façade. As such, comparisons can readily be made to determine whether, on the basis of the results at hand, there is, e.g., a smaller or a greater proportion of damage that occurs to for type X as compared to either Y or Z type bricks, whether, damage is more prominent or East versus other façade directions, or whether any given Block is itself more prone to having damaged brick units.

It is apparent from the results provided in Table 4 that Type X bricks are consistently failing in proportion to their numbers, suggesting that the mechanism of failure is systematic throughout the respective blocks and different directions. As well, on average, Type Y brick units are failing less than either the Type X or Z bricks. Thus the results do not support the notion that a greater proportion of Type Y or Type Z bricks are damaged as compared to Type X bricks; however, it is shown that the overall proportion of damaged Type Z brick is

Table 4 – Ratio of damaged bricks per panel by type to total number of bricks, by type, per panel (2015 results)

Type of brick	Damage proportions for Block 100				Damage proportions for Block 200				Damage proportions for Block 300				Average value
	E	S	W	N	E	S	W	N	E	S	W	N	Overall
Type X (main)	1.00	1.04	0.99	1.08	0.99	0.97	1.04	1.04	1.12	1.15	0.81	1.1`	1.03.
Type Y (rowlock)	1.22	0.89	1.00	0.56	0.56	1.00	0.89	0.78	0.00	0.11	0.00	0.22	0.61
Type Z (soldier)	0.60	0.60	1.20	0.40	2.00	1.60	0.60	0.80	0.80	0.00	6.00	0.60	1.27

greater than either the Type X and Y bricks. This is primarily due to the much heightened proportion of damaged bricks on the West elevation of Block 300 (6X that of all Type Z) as well as the amplified proportion of damaged brick on the East and South facades of Block 200, and to a lesser extent that of the West facade of Block 100; each of these values have been highlighted in the table.

With the exception of Type Z bricks for which a much greater proportion of bricks were found to be damaged (and perhaps corrosion is acting), it may be concluded, in general, that rebar corrosion is not be the prime contributor to the brick damage observed at the LTDLC complex (based on 2015 inspection results).

2.3 Identification of deterioration mechanisms and their impact

Despite the observations of brick failures in previous inspections, the underlying causes of the premature deterioration of the brick walls have not been previously investigated. This step is required for a clear understanding of the deterioration mechanisms in order to make a sound assessment of the deterioration rates and risks, and to propose cost-effective facade maintenance solutions to PSPC.

The wall panels incorporated prefabricated reinforced brick masonry panels, a type of construction that perhaps was not overly common for high-rise building structures built in the mid 70's. For instance, as shown in force the brick to split and fall off the wall, as observed and reported on several occasions by JCAL. With either a significant increase or decrease in temperature, the different rates of expansion or contraction between the brick and the mortar surrounding the brick may also cause shear stresses in the joints, creating cracks between the bricks. Should cracks form on the four sides of the brick, it will become unstable and loose, and may be at risk of failing. The rebar may not restrain any failed bricks given that the rebar is in the same plane as failed bricks.

The rate of this type of deterioration, if acting alone, is expected to be linearly proportional to temperature changes. When considering daily temperature changes (from direct sunlight to cooler night temperatures), the extent of this type of deterioration is expected to be larger on facades facing South than on those facing North. When considering annual temperature changes (from hot summer to cold winter temperatures), the extent of thermal movement deterioration may be large for all facade orientations. Numerical modelling undertaken at NRC-Construction is to provide more evidence, the results of which for a preliminary modelling study are described in Chapter 3.

and Figure 9, the wall panel assembly consists of a set of "layers" that include (from interior to exterior): (i) Interior grade gypsum panel directly affixed to; (ii) Reinforced concrete panel; (iii) Extruded polystyrene insulation; (iv) nominal (12 mm) air space, and; (v) prefabricated brick masonry cladding with embedded steel reinforcing bars located at the edges of window openings and panels. The prefabricated brick masonry cladding is affixed to the concrete panel with a series of shear connectors evenly spaced throughout the concrete panel.

It is supposed that the brick masonry clad pre-fabricated wall panels were cast on a level horizontally surface with the exterior brick facing downwards. The casting method of fabrication would have involved the combining of masonry units, mortar and grout into the prefabricated wall panel[6]. In general, such a casting method requires a form or an alignment device, some method of placing units and reinforcement, and a method for introducing mortar or grout. The usual practice is to place the units, either by hand or machine, and fill the form with a grout at atmospheric pressure or under moderate pressure. Jigs and forms provide for the alignment of the brick and the spacing for the joints.

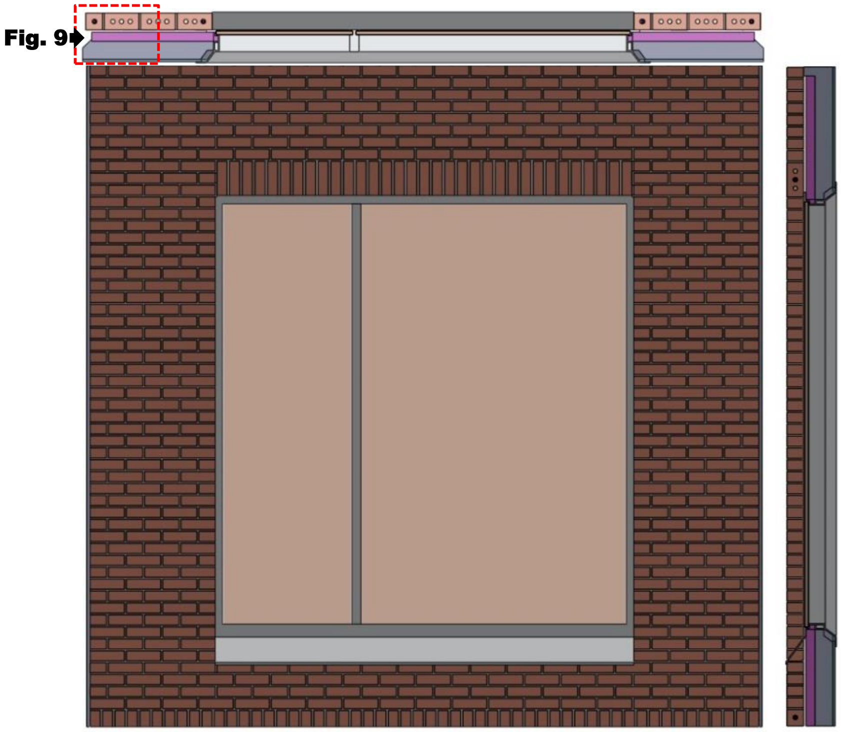

Figure 8 – Elevation view, and horizontal and vertical sectional views of prefabricated brick masonry single-window wall panel

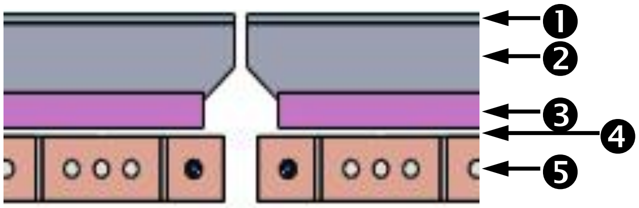

Figure 9 – Horizontal sectional view at joint between adjacent wall panels: (1) Interior finish – 11 mm gypsum panel; (2) 100 mm reinforced concrete panel; (3) Insulation – 50 mm extruded polystyrene; (4) Air space – 12 mm; (5) Exterior cladding – 90 mm reinforced brick masonry

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[6] Brick Industry Association, The (2001), Technical Notes 40 - Prefabricated Brick Masonry – Introduction; Reston, VA, USA, 11 pgs.

Several possible causes of deterioration are being investigated on the basis of materials taken from an actual wall panel specimen that had been extracted from the West face of Block 200. They include: (i) differences in rates of thermal expansion amongst brick units, epoxy mortar (grout) and steel bars; such differences can give rise to stresses and eventual cracking of the brick units and joints due to annual and daily temperature variations; (ii) corrosion of steel bars creating internal pressure and cracking of the surrounding bricks; (iii) moisture absorption and subsequent freeze-thaw action on brick units resulting in cracking; and (iv) stiffness of bricks and mortar which makes them brittle and subject to movement-induced cracking; (v) bowing of wall panels resulting in vertical cracks at the joints between bricks. Each of these causes of deterioration is further explained in the following sections.

Thermal expansion of bricks, mortar and steel — When two bonded materials have dissimilar rates of expansion, one material will evidently expand, or contract at a different rate than the other when subjected to temperature changes, eventually creating a plane of micro-cracks caused by tensile stresses in one material and compressive stresses in the other leading to failure along the interface between mortar and brick units.

Laboratory testing undertaken at NRC-Construction has shown that the brick units have a coefficient of linear thermal expansion that is 2 times lower than that of the mortar, and 3 times lower than that of steel. In this case, with an increase in temperature, the mortar and the reinforcing bar in the brick openings will expand to a greater extent than the surrounding brick. With 3 circular openings well aligned in the brick, a failure plane may also develop through the three holes and parallel to the face of the brick, and force the brick to split and fall off the wall, as observed and reported on several occasions by JCAL. With either a significant increase or decrease in temperature, the different rates of expansion or contraction between the brick and the mortar surrounding the brick may also cause shear stresses in the joints, creating cracks between the bricks. Should cracks form on the four sides of the brick, it will become unstable and loose, and may be at risk of failing. The rebar may not restrain any failed bricks given that the rebar is in the same plane as failed bricks.

The rate of this type of deterioration, if acting alone, is expected to be linearly proportional to temperature changes. When considering daily temperature changes (from direct sunlight to cooler night temperatures), the extent of this type of deterioration is expected to be larger on facades facing South than on those facing North. When considering annual temperature changes (from hot summer to cold winter temperatures), the extent of thermal movement deterioration may be large for all facade orientations. Numerical modelling undertaken at NRC-Construction is to provide more evidence, the results of which for a preliminary modelling study are described in Chapter 3.

(i) Corrosion of steel reinforcement — When steel reinforcement is exposed to moisture and oxygen, a protective corrosion layer will form on the surface of the bar and a passive corrosion rate will develop. When this passive protection layer is destroyed by exposure to aggressive ions such as chlorides or by concrete carbonation, an active and more aggressive corrosion rate will ensue. As a result, the rust accumulating around the reinforcing bar will occupy a larger volume than the volume of steel it replaces, thus increasing radial tensile stresses in the surrounding material – mortar or concrete – that eventually leads to cracking. Corrosion of steel reinforcement also weakens the bar due to a reduced cross-section.

The results from laboratory testing completed at NRC-Construction will permit determining the rate of corrosion of steel bar samples taken from the wall panel specimen; these will be provided in a final report. In the case where a rebar is embedded in the mortar inside a brick opening, the corrosion product forming around the rebar over time will create pressure in the brick, and may result in cracking of the embedded mortar and surrounding brick. The cracking will most likely be parallel to the rebar, i.e. vertical in normal horizontal bricks, and horizontal in the vertical rowlock and soldier bricks.

The rate of this type of deterioration, if acting alone, is expected to depend on the availability of moisture and the ambient temperature, since corrosion is activated by moisture and its rate increases under higher temperatures. When considering the building facade orientation, higher corrosion rates of the steel reinforcement may be higher on East and South facades, since East facades are more exposed to driving rain and South facades are more exposed to elevated temperatures from direct sunlight. This type of deterioration has been observed to be more frequent on East and South facades. Numerical modelling from which the effects of corrosion products on the adjacent mortar and brick elements can be discerned will provide more evidence and from which conclusions could be drawn as to the significance of this deterioration mechanism to that of the brick masonry panels.

(ii) <u>Moisture absorption and freeze-thaw resistance of bricks</u> — Porous materials when saturated and subjected to cycles of freezing and thawing may deteriorate as water expands to form ice inside the pores and creates internal pressures, should the water not be capable of readily escaping from the pores; this process may result in crack formation as the number of freeze-thaw cycles increases. It is generally understood that porous materials with well-connected pores may have increased resistance to freeze-thaw cycles since freezing water can expand without being constrained in isolated pores.

The results from laboratory testing completed at NRC-Construction are intended to demonstrate the resistance of the bricks to freeze-thaw action and from this infer as to whether the pore structure is, or is not, a well-connected network of pores on the basis of their freeze-thaw performance (poor performance indicative of a poorly connected network and good performance a well-connected pore structure). However it is not yet evident how many cycles these bricks can withstand under conditions that have prevailed at LTDLC over the years. The number and severity of the freeze-thaw cycles over the life of the LTDLC complex will be estimated to better understand the relative importance and the impact of this type of deterioration on the overall deterioration of the brick masonry wall panels.

The rate of this type of deterioration is expected to depend on the number of freeze-thaw cycles and the availability of moisture. Considering the building facade orientation, more severe deterioration due to freeze-thaw cycles may be found on East and South facades, since it is known that East facades of the complex are more exposed to driving rain than others, as this is the predominant wind-driven rain direction. Whereas, South facades are subjected to higher surface temperatures thus resulting in greater surface temperature differences over a daily cycle as compared to, for example, North facades. A large specimen assembly of several brick units and incorporating steel reinforcing bar will be tested at NRC-Construction under freeze-thaw cycles to provide more evidence of the response of brick assembly to freeze-thaw action and from which conclusions can ultimately be drawn.

(iv) <u>Stiffness of bricks and mortar</u> — A material with a high modulus of elasticity can carry high loads with only a small deformation. A side effect is that such type of material is typically brittle and may easily crack when deformations become too large, beyond their capability to accommodate strain.

Results from laboratory testing (Table 6) have shown that both the brick and mortar used have high values of modulus of rupture (Brick: 4.7 MPa) or tensile splitting strength (Mortar/Grout: 14.8 MPa). These materials may display very brittle behaviour, thus being prone to cracking when high forces and/or significant deformations are imposed on them. As a result, a small deformation (caused by thermal dilatation) may induce a flexural crack in the brick or a shear crack in the mortar joint between two adjacent bricks. Given that the mortar itself is stiff, it is also possible that loads and movement on one brick are directly transferred to an adjacent brick as opposed to being accommodated at the joint where the jointing material is less stiff, and capable of accommodating more strain. As a result of a stiffer, less pliable mortar, longer cracks may be created in the mortar joints and along a larger number of bricks.

This type of deterioration is inherent to the material, and its rate may depend on any combination of different types of deterioration that induce movement in the bricks. It is expected that much useful information on the nature of strains in the brick and mortar can be gained from completing numerical modelling simulation that will provide more evidence of the primary causes of deterioration in the brick panels and further inform on drawing conclusions as to their expected life.

(v) Bowing of wall panels — Bowing of wall panels has been observed and reported by CABA who conducted a structural review on the LTDLC complex in 1997. They indicated that all the brick masonry wall panels displayed bowing with amplitudes at the centre varying from 12.5 mm to 20 mm; interestingly, this is not immediately evident upon a cursory inspection of the panels from the exterior although bowing was quite evident in at least three panels of Block 100[7].

Bowing of the panels can impose unforeseen flexural movement on the brick masonry wall panels. As a result, vertical cracks may develop at the joints between bricks, at the brick itself, whereas horizontal cracks may develop at the joints between the bricks. Although the structural review undertaken by CABA in 1997 indicated that the observed bowing was within acceptable limits according to CSA A23.4 (1994), the assumed brittleness of the bricks and mortar, as indicated earlier, an unusual combination, may make the LTDLC brick masonry walls susceptible to premature cracking due to bowing, especially when compounded with other sources of deterioration.

Another question remains regarding the underlying cause of this bowing. Thermal effects are excluded since the bowing is evidently not reversible. Differential drying shrinkage is the suspected issue, as the concrete panel had been drying faster from the inside of the building than from the outside surface in contact with the extruded polystyrene insulation, thus resulting in the outward bowing of the wall panels towards the exterior (analogous to slab curling). Drying shrinkage occurs due to the loss of capillary water from the concrete pores to the drying outside environment during the curing period and its later service life, resulting in contraction. With the inside surface drying faster or more than the outside surface of the concrete panel, bowing of the wall will induce tensile stresses at the exterior surface, which may lead to cracking, warping, and deflection. Simple calculations and preliminary results derived from 3D finite element modelling have suggested that differential shrinkage might account for a fraction of the observed bowing. This type of issue, however, is not expected to worsen in the future given that the concrete has most likely undergone most of its drying shrinkage after 40 years. Numerical modelling results to completed by NRC-Construction will permit reviewing the evidence for differential drying shrinkage; this is to be covered in a final report.

3. Numerical modelling and analysis of bricks and wall panels (Task 1b)

To help better understand and confirm the structural and physical behaviour of the brick wall assembly and its underlying causes of deterioration, numerical analyses of brick and wall models have been conducted. The focus of the modelling was to investigate to what extent the observed points below played a role in the damaging the brick façade:

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[7] See § 4.5 Results of on-site inspection of Wall Panels

- Determine the stresses induced in the brick unit due to thermal effects as might arise due to changes in surface temperatures of the brick panel over the course of a year and given the marked dissimilarities in coefficients of thermal linear expansion amongst the brick, mortar (grout) and steel reinforcing bar, and as well, the inherent differences between, respectively, the tensile and compressive strengths of the brick and mortar (grout);
- Determine the stresses induced in brick units and mortar (grout) of an entire brick masonry cladding panel with a single window opening, an elevation view of which is given in Figure 8.

The commercial finite element modelling (FEM) software package *Diana V10.0* from *TNO*[8] has been used to conduct such type of analysis. Different models have been created, starting from a single brick unit to a brick masonry panel. Preliminary results from the FEM analysis are provided in the final sections.

3.1 Thermal stress analysis of brick unit

Starting with the simplest case, a clay brick unit was modelled including its three cores filled with epoxy-based mortar, and steel rebar embedded in the 3rd core. Since it is suspected that thermal contraction/expansion effects from large changes in ambient temperature are most likely the primary cause of deterioration, a thermal analysis was conducted and focused on the effect of bonded materials with mismatching coefficients of linear thermal expansion. The assumed material properties are given in **Error! Reference source not ound.**, which will be confirmed or updated when laboratory test results become available for samples taken from LTDLC. One property of significance in this analysis is the thermal expansion coefficient (CTE) of the brick, which is quite different to those of mortar and steel, where the CTEs of mortar and steel are about 2 and 3 times greater than the CTE of the brick, respectively.

Table 5 - Assumed properties† of brick and mortar materials for numerical modelling

Property	Brick	Mortar	Steel	Concrete
Mass density (kg/m^3)	2270	1910	7800	2300
Modulus of elasticity (MPa)	20,000	40,000	200,000	30,000
Poisson ratio	0.2	0.2	0.3	0.2
Thermal expansion coefficient (1/°C)	4×10^{-6}	8×10^{-6}	12×10^{-6}	10×10^{-6}
Direct tensile strength (MPa)	2*	6*	400	2

†To be confirmed/updated with laboratory test results from samples taken from LTDLC; *Taken as 40% of flexural strength

The brick model is shown in **Error! Reference source not found.** below, for which the finite elements were iven the properties indicated in Table 5 above. The brick dimensions are those of LTDLC: 193.7 mm in length (x), 92.1 mm in width (y), in 57.2 mm in height (z). The core diameter is 34.9 mm and core spacing is 48.4 mm from centre to centre. A 9.5-mm diameter rebar was also modelled at the center of the 3rd core (from the left) to represent those bricks reinforced with an embedded reinforcing steel bar.

In this simplified case, it is assumed that the movement of the exterior surfaces of the brick is not restrained and that there are no external loads applied on these surfaces; thus for this particular analysis, only internal stresses resulting from temperature effects were considered.

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[8] TNO: Netherlands Organisation for Applied Scientific Research; The Hague, Netherlands

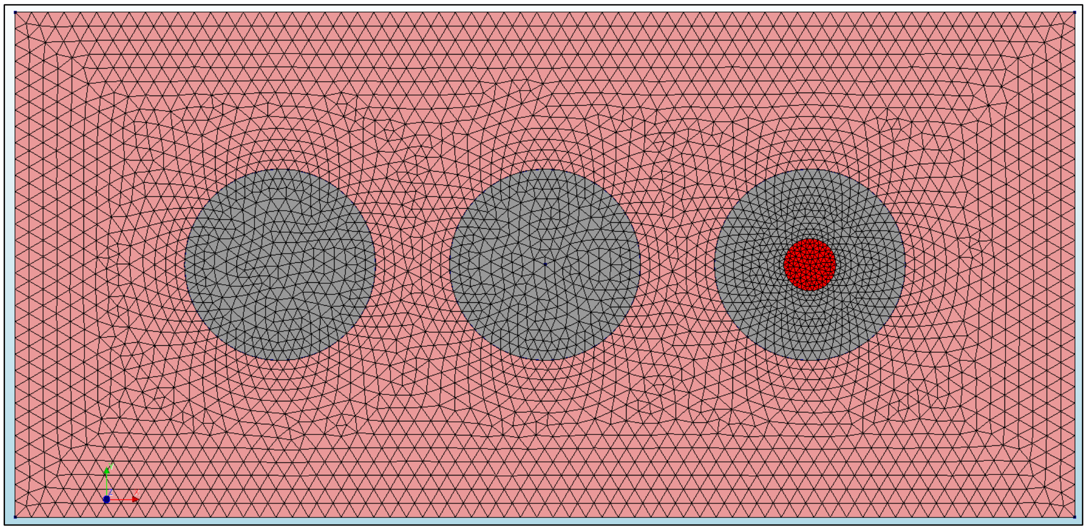

Figure 10 – 2D brick model featuring triangular plane-stress structural elements. Rebar is located in the circular opening on the far right along with the mortar; the other two openings have only mortar

Two separate load cases were considered:

- Case 1: 50°C temperature decrease (from 20°C during wall assembly to -30°C in winter)
- Case 2: 30°C temperature increase (from 20°C during assembly to 50°C in summer, exposed to sun)

These load cases are assumed to be the most probable extreme thermal loads that the wall assembly will likely undergo during a typical yearly cycle over its service life.

Figure 11 below illustrates the principal tensile stresses in the brick material resulting from a 50°C temperature decrease (relative to the assumed temperature when the mortar was first embedded). Two critical areas of high stress concentrations are observed that exceed the tensile strength of the brick (2 MPa), where finite elements with stresses equal or larger than the tensile strength are illustrated in red. These critical areas are: (i) the portion of the brick between two cores (direct tensile stresses in X direction); and (ii) the portion of the brick around each core (radial tensile stresses), where micro-cracks have likely formed in the brick. One can observe that the high stress area around the 3rd core (in red) is slightly larger than that around the 1st core, which is due to the more important contraction of the steel rebar.

Regarding the 2nd load case, Figure 12 illustrates the principal tensile stresses in the brick material resulting from a 30°C temperature increase (relative to the assumed temperature when the mortar was embedded). Again, one can observe the formation of high tensile stresses in two critical areas as defined above: (i) the portion of the brick between two cores (direct tensile stresses in Y direction), and; (ii) the portion of the brick around each core (circumferential tensile stresses). The presence of the rebar also generates some additional tensile stresses around the 3rd core.

The above (simplified) analysis confirms that thermal effects are a major cause of damage in the bricks, especially between the cores resulting in the formation of a weak failure plane that could eventually lead to brick splitting, as observed on many occasions by JCAL during field inspections (Figure 13).

Not only does the mortar have a much higher value for coefficient of linear thermal expansion as compared to the brick (i.e. 8.2×10^{-6} μm/°C vs. 4.1×10^{-6} μm/°C), but it also has a greater compressive strength (87 MPa) than the brick in tension (4.7 MPa); as such, it does not yield when it expands against the brick due to thermal thereby causing tensile stresses in the brick and the likely development of micro-cracks.

The presence of a steel rebar within the row-locks units that also differs in coefficient of liner thermal expansion further heightens the stress condition in the brick unit incorporating rebar. It is to be noted that in conventional brick masonry construction reinforcing steel is not typically used in row lock construction.

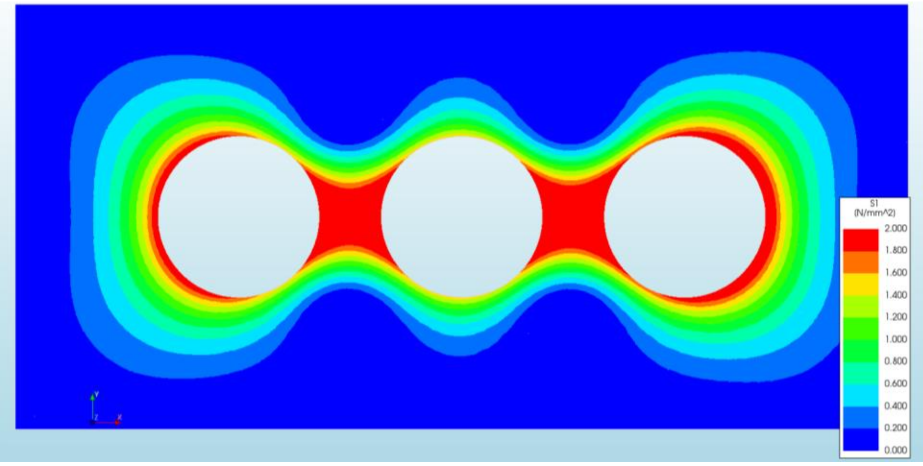

Figure 11 – Principal tensile stresses from a 50°C decrease in temperature (linear elastic analysis)

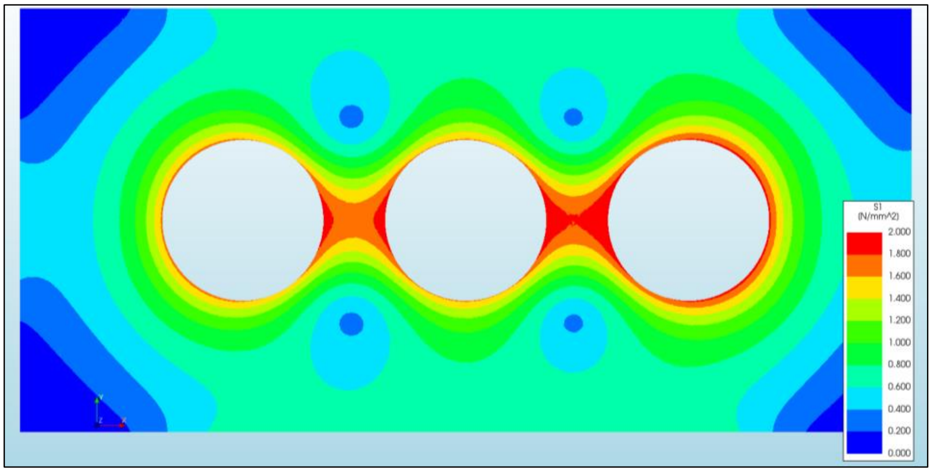

Figure 12 – Principal tensile stresses from a 30°C increase in temperature (linear elastic analysis)

Figure 13 – Brick splitting as observed by JCAL 2010

3.2 Thermal stress analysis of brick panel

A 2D brick panel with the window opening was modelled. In the case at hand, two simplifying assumptions were made in the modelling (making the analysis more conservative), including:

- Only bricks, mortar joints, and steel rebars were modelled given that the brick panel was supported by shear connectors to concrete panel;
- Brick cores were neglected (cannot be modelled in 2D when modelling in elevation view)

A thermal analysis looking at the effect of two bonded materials with mismatching thermal expansion coefficients was conducted, the results of which are given in Figure 14 to Figure 16. The model geometry of the brick panel is shown in Figure 14, representing a typical single window panel with overall dimensions of 3759 mm in width and 3718 mm in height. The window opening is 2353 mm in width and 2611 mm in height. The finite element meshing was generated with 2D plane stress elements, which were assigned the properties given in Table 5. No external loads were applied to the brick wall, thus only internal stresses resulting from temperature effects are considered in this particular analysis.

Figure 15 illustrates the principal tensile stresses calculated for a 50°C decrease in temperature. The results show that very high tensile stresses (exceeding the mortar tensile strength of 6 MPa) would localize in all horizontal and vertical mortar joints due to the significant movement restraint from the bricks, which are contracting at a lower rate. De-bonding of the bricks from the mortar joints would be expected in this case, and as observed by JCAL 2000 (Figure 17).

Figure 16 illustrates the principal tensile stresses calculated for a 30°C increase in temperature. The results show that small tensile stresses would be generated in the joints since in this case compressive stresses would dominate. However, moderate tensile stresses of up to 1.2 MPa would be generated in the brick units. From the analysis on a single brick unit it was evident that the mortar within the brick cores would significantly aggravate the problem; it could be inferred that most bricks in the wall panel would, as a result of a 30°C temperature increase, develop relatively high tensile stresses near the tensile strength of the brick (2 MPa).

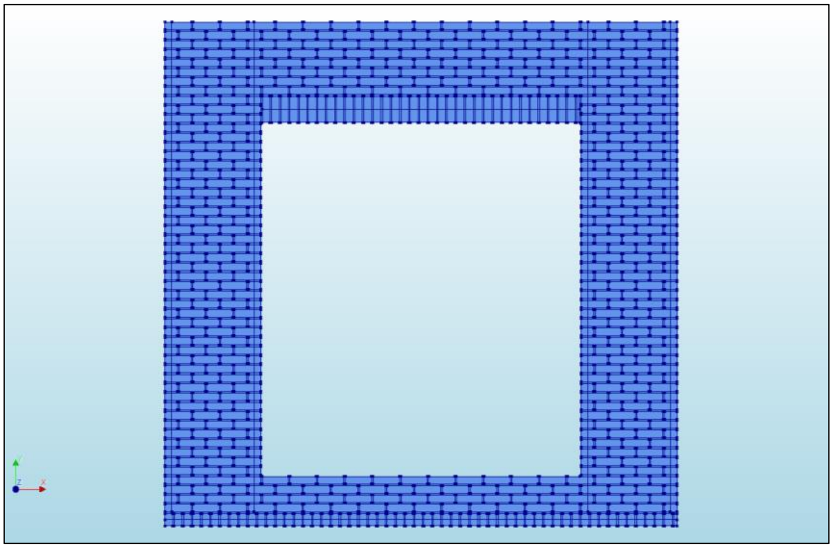

Figure 14 – 2D model configuration of brick masonry wall panel

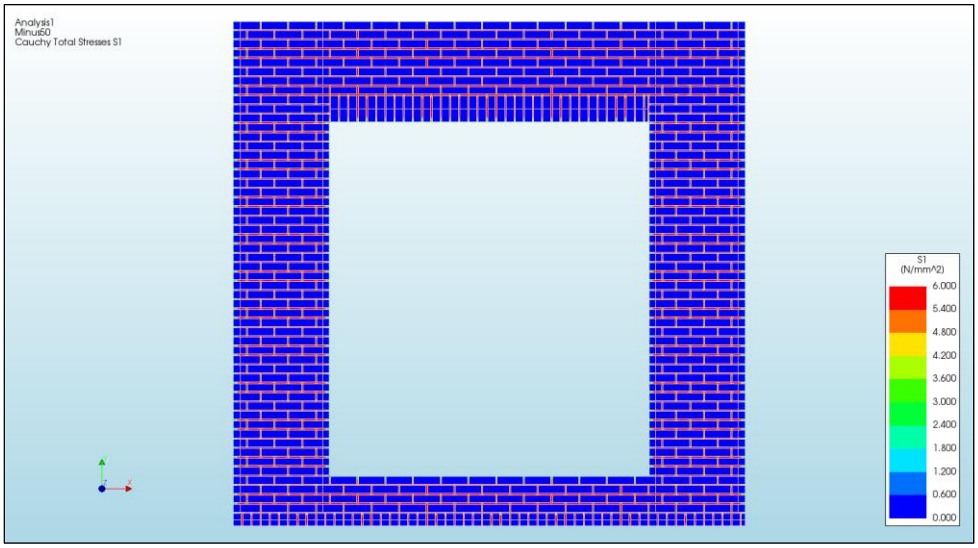

Figure 15 – Principal tensile stresses from a 50°C decrease in temperature (linear elastic analysis)

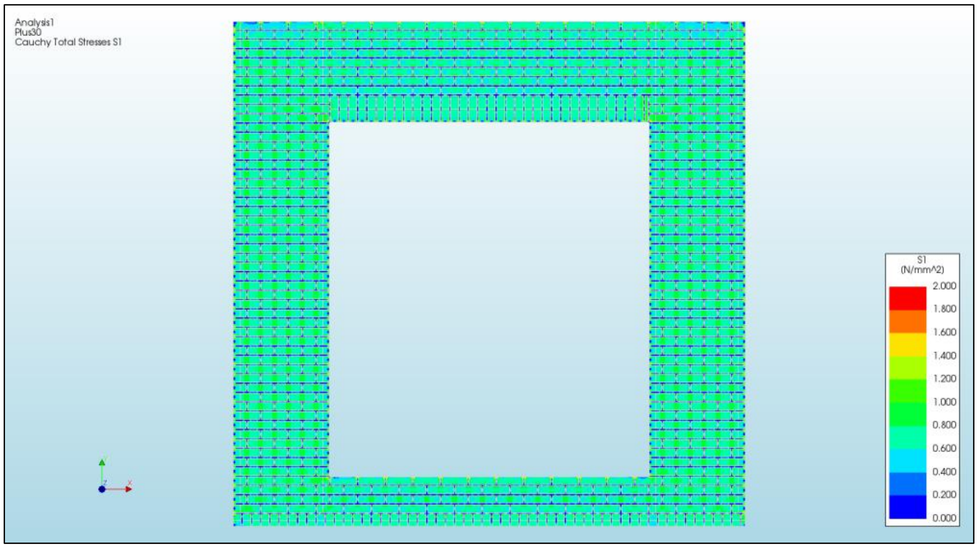

Figure 16 – Principal tensile stresses from a 30°C increase in temperature (linear elastic analysis)

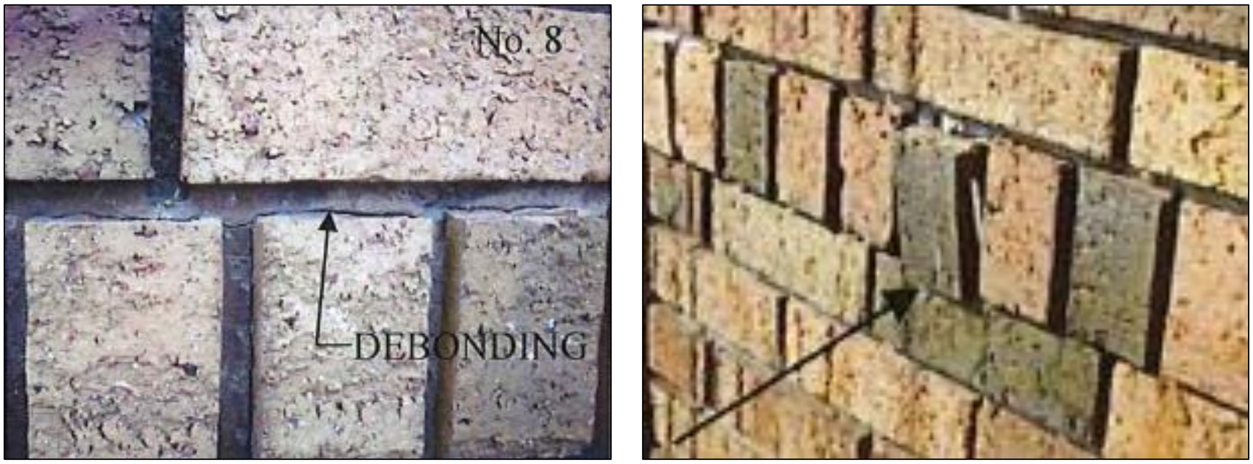

Figure 17 – Brick de-bonding and loosening as observed by JCAL (2000)

Finally, the same analysis on a 2D brick masonry cladding panel was completed with bricks and mortar of standard properties to show that for a more conventional construction, high stresses as were previously observed in the brick would in this instance not be present. Thus, for this exercise, the following changes were made to the properties of the brick and mortar (grout):

- Coefficient of linear thermal expansion of brick units: from 4 x 10^{-6} to 5.5 x 10^{-6}/°C
- Coefficient of linear thermal expansion of mortar (grout): from 8 x 10^{-6}/°C to 7.5 x 10^{-6}/°C
- Modulus of elasticity of mortar: from 40,000 MPa to 20,000 MPa
- No steel reinforcing in brick panel

Figure 18 shows the results for a 50°C temperature decrease, with tensile stresses in mortar joints (<1.8 MPa) being lower than the tensile strength of 2 MPa. Figure 19 presents the results for a 30°C temperature increase, with very low tensile stresses in brick or mortar (<0.2 MPa). This suggests that nearby buildings/houses built with conventional brickwork subjected to similar temperature changes may not be at risk of early degradation.

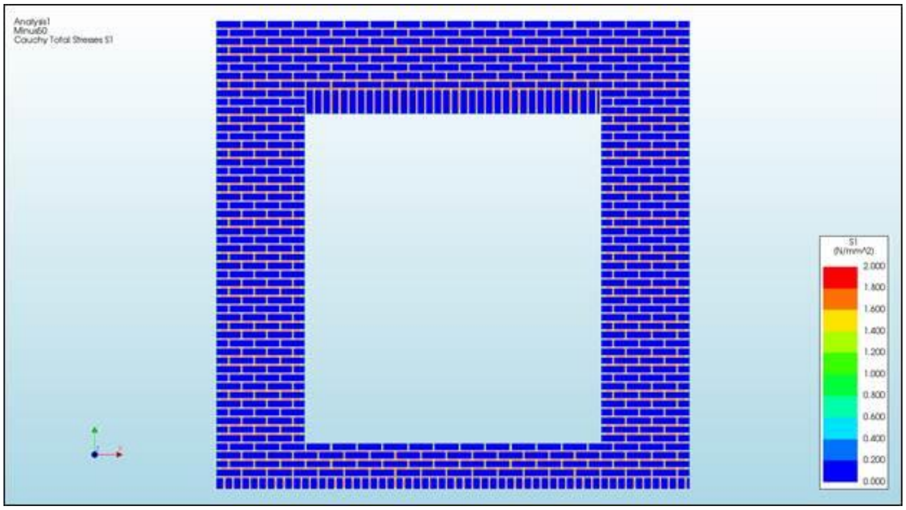

Figure 18 – Principal tensile stresses from a 50°C temperature decrease (linear elastic analysis) (assumed conventional construction)

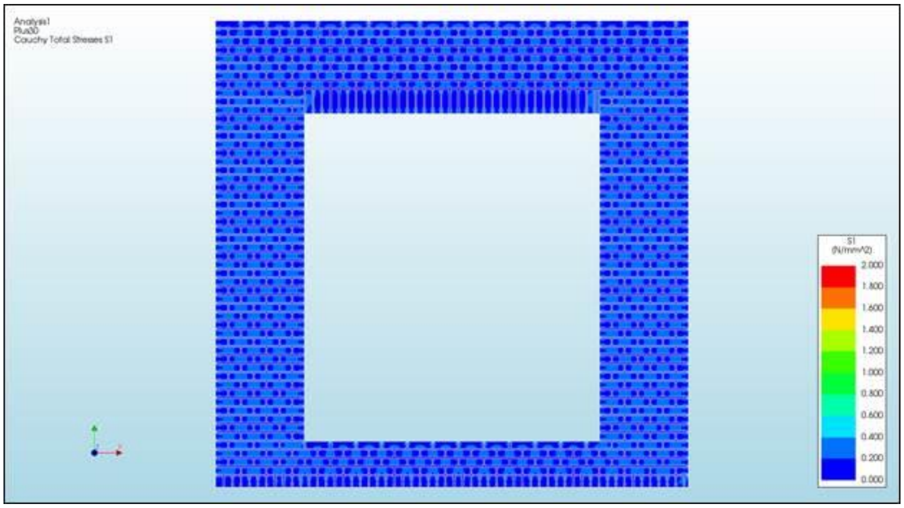

Figure 19 – Principal tensile stresses from a 30°C temperature increase (linear elastic analysis) (assumed conventional construction)

3.3 Preliminary observations on mechanism and extent of damage from numerical modeling results

Although the above thermal stress analyses covered only one aspect (i.e. thermal) of the many mechanisms that have actually combined to cause the observed damage at the LTDLC complex, it was clearly shown that thermal effects alone are sufficiently large to induce internal brick damage over just a single year cycle to eventually cause cracking and splitting of the bricks, as well as cracking and de-bonding of the mortar joints. It is also suspected that many bricks, which have not yet been identified as damaged bricks, may have significant internal damage (such as micro-cracks not visible to the naked eye) and in the short term, may be at risk of cracking or splitting.

In light of the above, it appears that the first and foremost damage mechanism that initiated wall deterioration observed at the LTDLC complex is thermal effects due to dissimilar coefficients of thermal expansion between the brick and mortar materials of the prefabricated brick masonry wall panels. With the induced micro-cracking in the bricks and mortar (aggravated possibly by their brittleness) due to thermal effects, it is supposed that moisture from driving rain has infiltrated the bricks and thereafter initiated other damage mechanisms such as freezing and thawing damage and eventually, corrosion of reinforcing bars. Bowing of the concrete panels walls appears to be due to differential drying shrinkage and therefore this action is separate from that occurred on the brick masonry façade.

3.4 Future planned numerical simulations

The numerical analysis is progressing and several other models and analyses are planned to permit confirming existing observations and to generate new evidence and to gain a better understanding of the deterioration mechanisms and their impacts. For instance, the above 2D single-brick and brick-wall models will be improved to include the effects of creep and cracking through a structural nonlinear analysis. This will provide a more accurate representation of stress development and crack formation in the brick wall. The adverse effect of corrosion (volume expansion) of the reinforcing bars embedded in the cores of the brick units will also be analyzed in addition to the thermal effects. A 3D model of the concrete backing is also being prepared to confirm the bowing of the panel and its severity due to differential drying shrinkage.

Numerical models of the entire wall assembly will also be completed to study other possible damage mechanisms such as freeze-thaw action following moisture uptake by the brick and mortar and surface temperature of wall panels. These will be carried out in the first instance acting separately and thereafter, simultaneously. Numerical analyses will include hygrothermal, heat transfer, and stress calculations.

4. Results of in-laboratory inspection of a wall panel & laboratory testing of wall components (Task 1c)

As part of a concurrent project (A1-007922 – LTDLC Materials Condition Assessment), one exterior wall panel at Les Terrasses de la Chaudière's complex was removed to assess removal methods for the anticipated future replacement of the envelope. The panel is a precast panel of a unique design made of brick veneer, insulation and concrete backing. PSPC planned to have this panel analyzed to identify the location of steel reinforcement (rebars) in the concrete, their corrosion condition, and material composition and strength, and other physical properties; such information is to provide insight into failure mechanisms of the bricks and investigate the possibility of retaining the concrete backing should there be interest in replacing the current brick veneer with another cladding. The National Research Council Canada proposed a comprehensive analysis of the panel, aiming to gain experience and knowledge that is most relevant to understanding the durability of the materials and degradation mechanisms.

Thus the concurrent project had three primary objectives:

1. Precise identification of rebars in concrete, their strength and corrosion condition;
2. Brick testing that included assessing moisture movement properties, compressive strength, resistance to freeze-thaw cycling, thermal properties, and materials analysis of the mortar that held the bricks;
3. Establishing basic properties and durability features of the concrete.

4.1 Identification of rebars in concrete and their corrosion condition

A number of tasks will be completed to identify the size and location of reinforcing bars in the brick masonry veneer and concrete wall panel and that will allow comparison with that found in the relevant structural drawings; this will help ensure completeness of the configuration when undertaking FEM of the panel; these tasks include:

(i.) Identification of the rebars (and sizing) in concrete and their location within both the concrete panel and the brick veneer;
(ii.) Completing half-cell potential testing (ASTM 876) which permits defining the level of corrosion as well as corrosion rate of rebars in the areas that show the most deterioration.
(iii.) Undertaking tensile strength testing (ASTM 370) of 4-6 pieces of rebar to determine its strength.

It is worthwhile noting that the results obtained from corrosion testing of the rebars in the wall panel that was delivered to NRC would not necessarily be representative of the "average corrosion condition" of all wall panels and especially not of those wall panels that have shown more advanced deterioration due to corrosion.

4.2 Brick Testing

As was the case for reinforcing bars, brick masonry units and mortar will also be tested to permit characterising their primary physical properties; this includes:

(i.) Testing to characterize the basic moisture movement properties of the brick and its capacity to absorb and release water; this will inform on the freeze-thaw performance of the brick units and that includes the following tests, undertaken in accordance with CSA A82:
  - Density (kg/m^3);
  - Water saturation coefficient (C/B), which is a measure of the amount of water absorbed by a brick unit in cold (C) water versus boiling (B) water and permits characterizing the brick's pore structure. Some research has been done to identify frost susceptible bricks to this ratio so the results from this test will allow defining the susceptibility of this brick to the effects of freeze-thaw action.
  - Initial Rate of Absorption (IRA) measures the amount of water taken up by the bedding plane of a brick in 1 minute.

(ii.) Compressive strength of the brick units and as a system.
(iii.) Freeze-thaw durability testing (CSA A82) provides a laboratory test method that assesses freeze-thaw durability. While not a field representative test procedure, this test will nonetheless help determine if the brick can still provide the minimum level of service required by the standard.
(iv.) Thermal Mechanical Analysis testing of brick samples by heating and cooling the sample permits determining the coefficient of thermal expansion of the brick material.
(v.) Material analysis of the mortar used in the brick masonry assembly. Thermal gravimetric analysis and x-ray diffraction can be used to identify the components in this mortar (Portland cement, lime, aggregates, and presence of organic materials (e.g. polymer). Although this testing may indicate that

there are organic materials in the mortar, another test would be needed to identify the type of polymer material in the mortar.

4.3 Basic properties and durability features of concrete panel

Testing of the concrete will be carried out to assess its current condition as well as the potential for corrosion to be ongoing in the concrete panel. The work includes the following tasks:

(i.) Assessing chloride profile of concrete (ASTM C1152) and carbonation depth, which are the two key factors for corrosion and assessing the risks of corrosion formation of the rebar in the future;

(ii.) Determining basic physical characteristics of the concrete that includes compressive strength (ASTM C39), absorption and density (ASTM C1754), pulse velocity (ASTM C597) and concrete resistivity;

(iii.) Determining the air content in the concrete by means of a linear traverse analysis (ASTM C457).

4.4 Wall Specimen

The wall specimen and parapet wall (which is just above the wall panel) was delivered to NRC on April 22, 2016. To facilitate delivery, the panel was cut into pieces of which there were 7 pieces delivered. Upon delivery the various segments of the original wall panel were laid out in the configuration of the wall panel itself; Figure 20 shows the wall panel as delivered to NRC.

Figure 20 – As received LTDLC wall panel on the ground

Beyond the basic tests previously described, a second series of tests were considered following delivery of the wall panel. This additional testing was undertaken as part of the present project (A1-008997-02) related to the long term risk assessment of the wall panels to help further understand the damage mechanisms that resulted in the deterioration of the wall panels. This series of tests were more structural in nature as compared to those tests previously undertaken that relate to notional material property assessments. That said, there was an opportunity to assess the physical properties of the mortar used in the wall panels. This would provide a useful link to possible damage mechanisms of the panels themselves.

Mortar properties – Typically, it is difficult to test physical properties of mortar retrieved from an existing structure. Thin mortar bed joints are not generally large enough to provide reasonable test specimens and the mortar is often chipped out to retrieve brick specimens leaving little material from which to prepare a useful test sample. The brick voids also typically have only a small lump of unconsolidated mortar squeezing in from the bed joints which render it of little value in terms of a test sample.

In this instance, Figure 21 shows a typical cross section of the brick that was removed from the wall with the mortar found to be completely filling the voids in the brick units. This is likely due to the construction technique of fabricating these wall panels on the horizontal and, once they has sufficiently cured, tipping them up to make them available for transport to the site.

One inch (1-in.) diameter mortar specimens were retrieved using a coring bit applied between the units as illustrated in Figure 21 and shown in Figure 22**Error! Reference source not found.**. The mortar samples hat were extracted in this manner were used to test for compressive strength, Young's modulus, absorption, density and coefficient of thermal expansion of the mortar.

Structural Assembly Testing – The brick panel assemblies were themselves quite resilient this owing to the strength of the mortar that had been used for this pre-cast construction technique. As a result, further testing of the brick-mortar interface was possible. This included determining:

- Modulus of Rupture strength between the brick and mortar which would provide some values for the bond between the mortar and brick units,
- Compressive strength (f_m') and Young's modulus (in compression) of the brick panel system; and,
- Young's modulus of the brick and mortar units would feed into the numerical modelling outlined previously in the report.
- Uni-directional freeze-thaw resistance of a group of panels would give a metric of the durability of the assembly.

Figure 23 shows a wall panel installed in the unidirectional freeze-thaw cabinet undergoing a thaw cycle. The unidirectional freeze-thaw test is an NRC modified test protocol based on a RILEM[9] standard that NRC has used for many years to assess the durability of mortars. Generally it is used as a comparative test – it permits reviewing results of different mortar mix designs with the intent of finding a product offering the best performance as compared to perhaps a range of products tested. However, the test can also provide some qualitative data on the likely performance of an existing mortar for the wall panel provided.

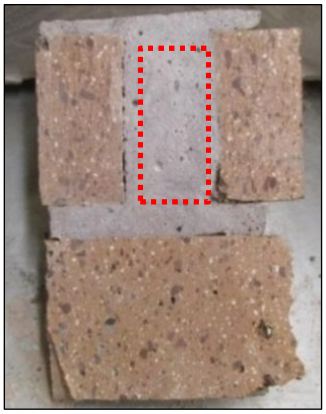

Figure 21 – Cross-sectional cut of brick removed from wall panel, displaying fully filled void spaces

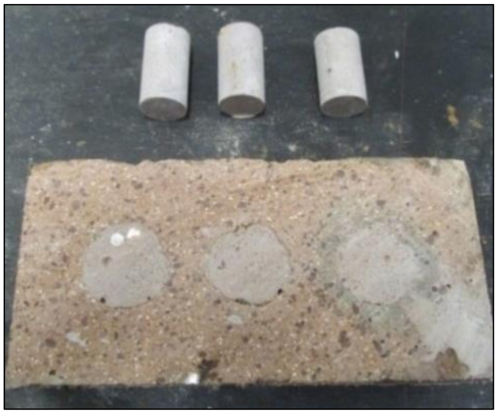

Figure 22 – Sectioned brick from wall specimen showing fully-filled voids and cored mortar samples

Figure 23 – Unidirectional freeze-thaw chamber during a thaw cycle with a wall panel installed

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[9] RILEM: International Union of Laboratories and Experts in Construction Materials, Systems and Structures

The test is undertaken in an environmental chamber where all but the front face of the wall is insulated from the chamber's ambient conditions. The temperature in the chamber is cycled and the freezing plane (delineates the portion of brick assembly that is frozen) is made to pass through the wall from front to back just as it would experience in the field. The thaw cycle "washes" the wall with water down the exterior face – again, thawing the sample from front to back. As per the standard, mortars that survive 24 cycles of this test should be able to survive exposure to climatic conditions as occur on the vertical exterior surface of walls, and the top portion of which is protected by means of flashing or an overhang. The results derived from assessing the physical properties of all materials that comprise the wall panels from both projects (i.e. A1-008997 and A1-007922 / LTDLC – Materials Condition Assessment) is provided in Table 6.

Table 6 – Material properties of components of wall panels (as of present date (June 1/2016)*

Material	Test Method	Result
Rebar	Tensile strength (ASTM 370)	N/A
	Young's modulus	N/A
Brick	Absorption (CSA A82)	3.5%
	Density (CSA A82)	2260 kg/m^3
	Initial rate of absorption (CSA A82)	0.14
	C/B ratio (CSA A82)	0.87
	Compressive strength (CSA A82)	99 MPa
	Modulus of rupture (CSA A82)	4.7 MPa
	Thermal coefficient of expansion	4.1 x 10^{-6} µm/°C
	Freeze-thaw performance(CSA A82)	N/A
Mortar (grout)	Absorption (ASTM C1403)	9.6 %
	Density (ASTM C97)	1911 kg/m^3
	Compressive Strength**(ASTM C780)	86 MPa
	Splitting tensile strength** (ASTM C780)	14.8 MPa
	Thermal coefficient of expansion	8.2 x 10^{-6} µm/°C
	Young's modulus*(ASTM C469)	N/A
Concrete (backing panels)	Absorption (ASTM C1754)	4.4 %
	Density (ASTM C1754)	2280 kg/m^3
	Compressive Strength** (ASTM C39	32 MPa
	Splitting tensile strength**(ASTM C496)	N/A
	Rapid Chloride permeability (ASTM C1152)	Low
	Chloride content (ASTM C1152)	0.04%
	Air content (ASTM C457)	6.34%
Composite (brick and mortar)	Flexural bond strength(ASTM 1072)	2.6 MPa
	Young's modulus (ASTM C469)	23 GPa
	Compressive strength (f$_m$')	58 MPa
	Unidirectional f/t (NRC test protocol)	N/A

N/A: Results not yet available; *Testing as relates to project NRC A1-007922 is on-going; results to be updated as they become available; **Denotes non-standard test specimen

4.5 Results of on-site inspection of wall panels

A preliminary on-site inspection of the wall panels was carried out on Thursday, 29 July 2016. The intent of this inspection was to observe first hand, the state of condition of the brick veneer wall panels from points of access to Block 200 at the base of the building (atop the sidewalk pedestrian protection) and at the 11th floor level; these particular location were chosen for ease of access. As well, a walk-around was completed to gain some appreciation for the location of pedestrian protection placed at the perimeter of the building complex (Figure 24) and to review the state of condition of the wall panels as could be gained from the ground level, examples of which are given in Figure 25.

Figure 24 - Examples of pedestrian overhead protection located at the perimeter of TDLC.

Figure 25 – Examples of repairs to brick units and brick veneer assembly conduced on East (Left) or to be completed on North (Right) façade of TDLC Block 100.

Photos of elevations of Block 200 showing the East façade (levels 11 to 25) and in which recent repairs to the brick façade are evident are given in Figure 26 and Figure 27. In Figure 26, the East facing facade from levels 11 to 25 are apparent and in which can be seen a number of instances where repairs have been completed; this is more clearly evident for repairs undertaken on levels 7 to 10 where the differences in tint of the bricks

Figure 26 –Elevations of Block 200 showing East façade of levels 12 to 25 (left) and details (right) of recent repairs along levels 7 to 10

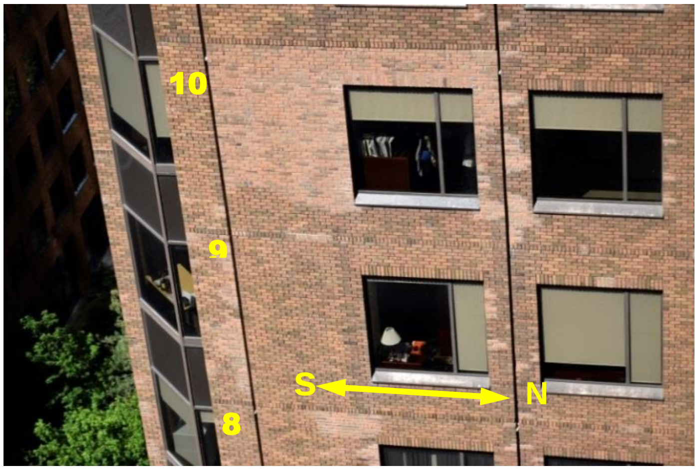

Figure 27 – East façade elevation, Block 200 showing extensive repairs to brick façade at level 8, but particularly at level 9

provides evidence of recent repairs on wall panels where the lighter hue indicates newly repaired brick. In Figure 27 can be seen the extensive repairs to the brick work undertaken on a panel located on the East façade of Block 200 at level 9; this panel is located towards the South side of the East façade.

In Figure 28 are photos of the West facing elevation of Block 100 showing the roof level (level 11) to Level 14. Evidence of brick fracture at panel joints is given in the top-right photo whereas the bottom photos provide details of brick spalling on East face of Block 100. The spalling of the brick facia is likely due to freeze-thaw action on the brick. During rain events, water run-off from the window sill migrates downwards and wets portions of brick beneath the sill making these locations more susceptible to freeze-thaw action.

Further evidence of brick failure at a panel joint is provided in Figure 29 in which the failure of a half brick unit is shown in a set of three photos; the upper left-most photo shows the location of the failed brick unit in relation to the panel joint, a detail of which is given in the adjacent photo on the left. The apparent damage to the brick unit is shown in detail in Figure 29 on the lower left; the damage is likely due to dissimilar values of coefficient of thermal expansion between brick and mortar; the mortar is seen to be completely intact.

Evidence of bowing of the concrete wall panels is shown in Figure 30. The left photo shows that of a South facing wall of block 300, whereas the right photo that of a West facing wall of the same Block. The bowing was apparent only on broader panels such as those having 2 windows; this effect was not wide-spread as was suggested in previous reports.

Additional results of the on-site and in-situ inspection of wall panels are being complied and are not yet available although inspections are taking place; these are to be reported in a final report.

Figure 28 - Photos (Top-left) of elevation of West facing façade of Block 100 showing Roof (level 11) to Level 14; (Top-right) Evidence of brick fracture at panel joints; (Bottom photos) Details of brick spalling on East face of Block 100; Evidence of spalling of brick facia, likely due to freeze-thaw action; water run-off from window sill above wet portions of brick beneath sill making these locations more susceptible to freeze-thaw action

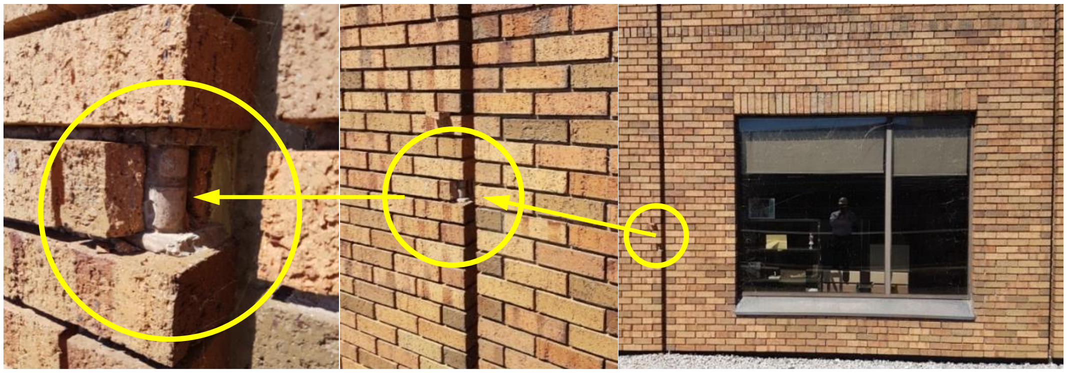

Figure 29 – Evidence of brick failure at a panel joint; failure of half brick unit likely due to dissimilar values of coefficient of thermal expansion between brick and mortar; mortar is seen to be completely intact; no degradation of mortar evident

Figure 30 – Evidence of bowing of concrete panels; clearly evident only on panels having 2 windows

5. Risk management of falling bricks from building facades (Task 2)

This section deals with risk management of the prefabricated wall panels of buildings that are part of Les Terraces de la Chaudière (LTDLC) building complex. NRC undertook a number of tasks to complete a Risk Assessment (RA) of LTDLC brick masonry wall panels based on the observed deterioration of the panels. The risk assessment concept was based on the combination of three components: Sources of hazard, vulnerability of the envelope, and consequence of failure.

In this section an overview is provided of the methodology used for risk management as described in ISO 31000, and thereafter, a risk model is defined that forms part of the management process. Following which, recommendations are presented for risk mitigation measures. These recommendations are based on a review of literature consisting of the reports submitted to NRC by PSPC (list of reports provided in Appendix B). It is expected that the recommendations provided in the current report will be updated as more in-depth information becomes available and can be used to further inform the risk management process as the study progresses.

5.1 Risk methodology

In the ISO 31000 standard[10, 11] a useful framework for risk assessment and management is provided. The framework consists of the following items: risk identification, risk analysis and risk evaluation. This framework is generic and it is the responsibility of the user to apply the different steps depending on the application and context in which the risk management is required.

In respect to the present project that focuses on the failure of brick masonry facades of the LTDLC, it is first necessary to define the context under which to complete the risk assessment. In this instant therefore, the ultimate and unique risk being considered is the risk of falling brick(s) from the brick masonry facades and their potential consequences to arising harmful effects on pedestrians who may be in proximity to the base of any of the building facades. In this study, the risk of failure of the concrete walls is not considered, as

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[10] ISO 31000:2009, *Risk management – Principles and guidelines*

[11] ISO/IEC 31010:2009, *Risk management – Risk assessment techniques*

previous structural inspections have confirmed the structural integrity of the walls according to the building code at the time of construction.

In the subsequent sections, and in the context of the current LTDLC case study, the steps in completing the risk assessment process are described and consist of: risk identification, risk analysis, and risk evaluation

5.1.1 Risk identification

The risk identification process consists of identifying all possible scenarios leading to the ultimate risk which is the risk of falling brick(s) from the brick masonry façade. This is to be completed without explicitly estimating either the probability of occurrence of events or their resulting consequences.

The process includes identifying the causes and sources of the risk events, situations or circumstances that may cause this risk to arise (Figure 31). In the case of the LTDLC building complex, both the deterioration of the brick masonry facade and repairs to the facade have taken place over the past several years (~ 20 years), as previously reported.

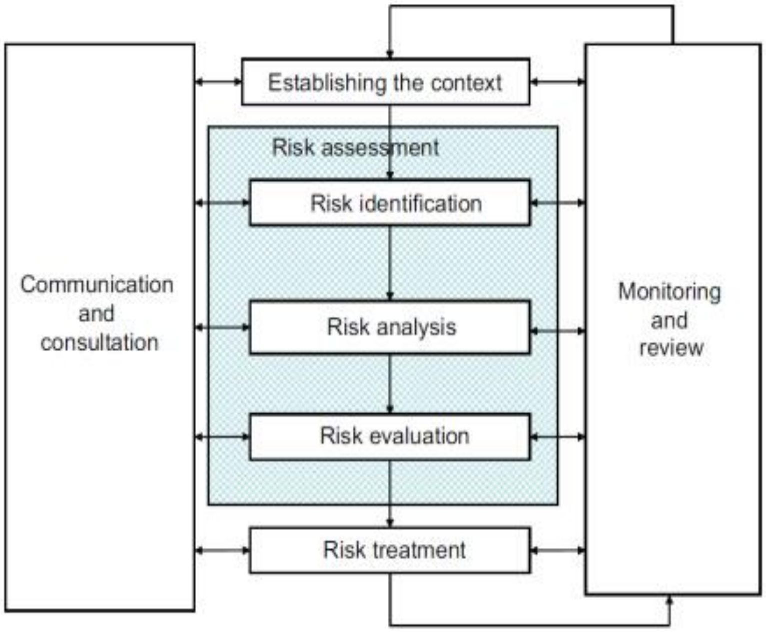

Figure 31 – ISO 31000 Risk management framework (10)

The information provided in the existing inspection reports permits investigating the pathology of deterioration of the brick masonry. Several possible causes were discussed in Chapters 1 and 2 of this report (e.g. thermal expansion, freeze-thaw cycles, and corrosion of steel reinforcement).

It is suggested in ISO 31000 that there are different techniques to improve the accuracy and completeness of risk identification, and that includes brainstorming using the Delphi methodology and fault tree analysis.

5.1.2 Risk Analysis

This step has to do with estimating the probability of occurrence of deterioration scenarios and their related consequences. Risk analysis can be undertaken with varying degrees of detail, depending on the availability of data and resources. Analysis can be qualitative, semi-quantitative or quantitative.

An example of a quantitative concept to determine the probability of occurrence of harmful effects or loss due to the occurrence of the risk event can be written as follows:

$$\Pr(Harm) = \sum \Pr(\text{brick fall}).\Pr\left(\text{not stopped}/\text{falling}\right).\Pr\left(\text{Harm}/\text{not stopped}\right). \qquad \textbf{Equation 1}$$

Where:

Pr(Harm) :	Annual probability of occurrence of harmful effects
Pr(Brick fall):	Annual probability of brick falling from a specific facade panel
Pr(not stopped/falling):	Conditional probability of brick landing or reaching an area having the presence of pedestrians.
Pr(Harm/not stopped):	Probability of harmful effects occurring to pedestrians assuming a brick lands in an area having the presence of pedestrians (i.e. this probability has to do with the frequency of pedestrians in that area).

Harmful effects that may arise from bricks falling on pedestrians are mainly concerned with the occurrence of injuries or fatalities. If costs are to be considered, other types of consequences can be added, such as: harm to the organization's reputation, accelerated local deterioration due to delayed intervention, user costs due to road closure, cost of immediate intervention and repair, and other related consequences.

Being the dominant risk, harm to public is the only major risk that is considered in the proposed risk model. In the instance where overhead protection is to be extended to all the remaining areas that surround the buildings of the complex, the only residual risks that can be deemed as non-acceptable are:

- Risk of brick fracture, and "fall out" where thereafter the brick would strike a window sill or narrow roof parapet, and thereafter deflect away from the building face descending downwards and outside a protected area ,thereby potentially causing harm;
- Risk of splitting of several bricks in a large panel for which the overhead protection would be inadequate against puncture.

Taking into consideration the amount of uncertainty in either of these cases, a quantitative evaluation of this situation is not yet possible. Nevertheless it can be used to establish a comparative means of rating the risk through a suitable estimate of different risk factors and from which a qualitative evaluation can be completed. It is possible that a risk model based on a semi-quantitative analysis could be completed and that would draw upon results from both the laboratory testing and numerical modeling being completed in this project.

5.1.3 Risk evaluation

The risk evaluation step is useful in that it allows decision makers to find a solution that is acceptable to all parties involved. Of course, one possible result from completion of this step is that the risk analysis needs to be repeated with more detailed representations of the system, improved models and different values for parameters and as such information becomes available to the study. Another possible result is that the risks as determined from the evaluation process are acceptable and no further review of possible interventions are warranted. There could also be a follow-up of the evaluation with cost-benefit analysis of the different mitigation measures that may lead to the same degree of risk (e.g. using a risk grid as shown in Figure 34).

5.2 Proposed risk model

The proposed risk model is based on rating different "vertical sections" of each building elevation in terms of the potential for generating a hazard to the public (i.e. where by "public" one refers to any pedestrians in proximity to the base of the buildings). In order to do so, an assessment of the overhead condition will require the vertical sectioning of all elevations. In other words, an assessment of the potential landing areas for bricks will allow identifying, as a first step, sections at the base of buildings with nominally the same risk to the public, referred to in this report as Iso-risk areas. This will include assessment of the performance of the overhead protection (e.g. shape, width, material, strength), barricaded areas, local public presence and traffic frequency (side walk, bus station, building entrances, and other similar features identified) and building height (the vertical red lines in Figure 32 and Figure 33 offer an example of Iso -risk building sections). Once all Iso-risk sections are identified, a risk rating can then be completed to determine those sections with the highest risks. For each section, a semi-quantitative risk assessment can then be achieved by combining the likelihood of falling bricks and its potential consequence as a hazard to the public; probability functions of distances from buildings facades should brick units fall are provided in Appendix C.

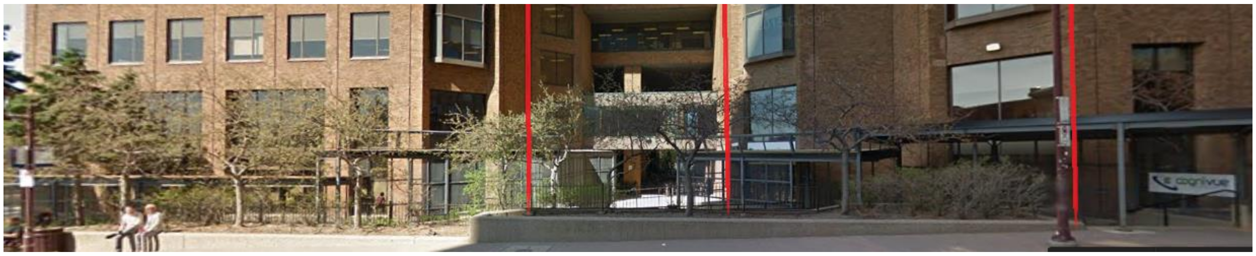

Figure 32 – Example of Iso-risk sections

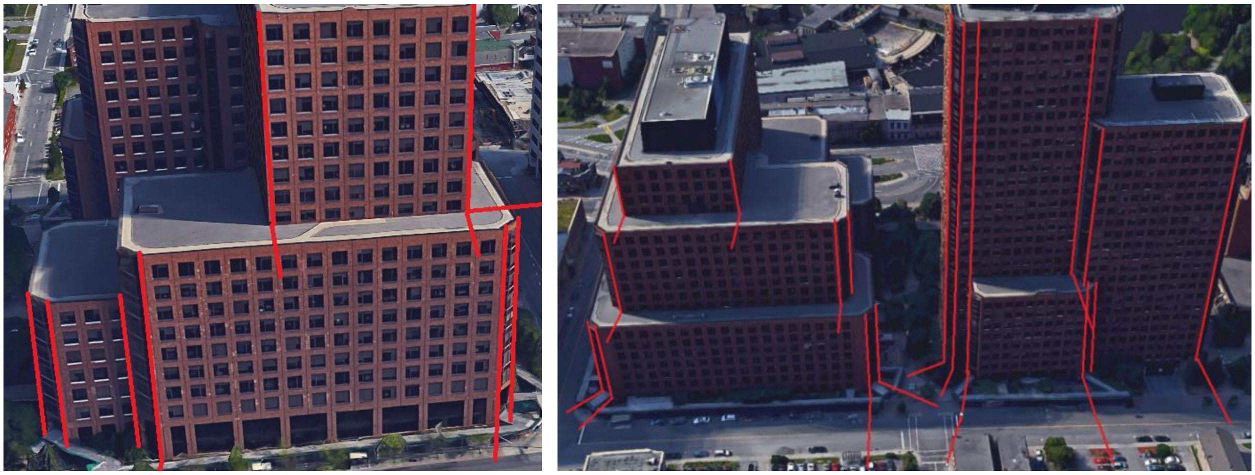

Figure 33 – Overlapping landing areas

5.2.1 Assessing the likelihood for bricks to fall from facade panels

The assessment of likelihood for bricks to fall from a masonry panel for each building facade section is based on the information available from different factors, which are:

- The number of bricks deteriorated or repaired in the panel sections as obtained from JCAL's 2010 report[12] and where quantitative information is available.
- The number of bricks damaged or repaired in the panel sections from JCAL's 2010[5] report and JCAL's 2015 report[13] and where quantitative information is likewise available; this indicator is to be normalized by section width.
- Percentage of "damaged brick with possibility of re-direction" (Type Z and at window edges): This is considered as a separate indicator given that: (i) it could represent a greater risk for a brick to fall from any of those locations, and; (ii) it could be related to a specific type of failure (e.g. greater exposure of window vertical edges and lintels (soldier bricks) to external environment conditions).
- The overall condition of panel sections[6]: This would involve one's best judgment concerning the current condition of the section. (i.e., history of specific problems recorded; percentage of panels deteriorated per facade, moisture migration paths and drainage, efflorescence of brick units). For the present, this factor is estimated based on the ratio between the numbers of panels presenting any type of damage in relation to the total number of panels in the section. This indicator should take into account the period between inspections; therefore, the number of damaged bricks should be divided by the duration between the last two inspections. The accuracy of estimating this factor would be enhanced whenever laboratory results and further investigations on the pathology of deterioration of the brick façade are completed.
- Bricks splitting parallel to the face of the panels (if any location is currently identified or might be detected in the future). This hazard can be classified as high risk, since the falling trajectory of a split portion could be more random due to air resistance and the shape of falling portion, and it would have more energy when hitting the overhead protection, and which may not be designed to withstand such hazards).
- Exposure to severe environmental factors such as, solar radiation, wind-driven rain, freeze-thaw effects.

In Table 7 is shown the primary factors assumed to be the most critical in estimating the likelihood[14] of bricks to fall from the facade panels. Other factors can subsequently be added (changed or removed) over the course of the study as more information becomes available, and if deemed necessary based upon expert judgement.

The weighing factors that will be provided in Table 7 are positive integers that:

- Represent the relative importance of the factor considered independently of the section;
- Take into account uncertainty bias when information is not available; i.e., it will be set to its minimum value (1) whenever the level of confidence in the presumed indicator is minimal (i.e., 1 means minimal contribution to risk rating).

Regarding the normalized rating, the minimum value for each factor is equal to 1. This represents the case where no or minimal deterioration was observed or when the exposure to a harsh environment is assumed to be minimal or unlikely (e.g. interior elevations; shaded areas; rain flashing installed).

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[12] JCAL's 2010 report

[13] JCAL's 2015 report

[14] Likelihood has ranking significance rather than probability estimation

Table 7 – Likelihood assessment process[15]

(Table shown illustrates values required for factor identified – not yet complete)

	Likelihood factors		**Initial rating**	**Weighing factor**	**Rating (rating x weight)**	
	Info from JCAL 2010 report	To be completed				
JCAL 2015 report	Number of damaged bricks (2015)	137	0.1	25		2.5
	% brick failure with high Prob. of deflection[16]	63/137	0.46	5		2.5
	Overall section condition[17]	72/102	0.71	5		3.5
	Exposure to wind (east, South, obstacles, …)	Not yet implemented				
	Exposure to precipitation					
	Exposure to solar radiation					
	Likelihood of brick splitting in groups					
	Total					8.5

5.2.2 Assessment of consequence of harmful events

In this study, the assessment of consequences arising from harmful events is directly related to the areas where bricks may potentially land once ejected from the facade panel (

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[15] See Appendix D.3 for more details about the likelihood estimation

[16] Percentage of both damages: Type Z damage and damages on windows vertical edges.

[17] In the meantime, this indicator is assessed based on the percentage of “panels” defected

Table 8). The primary factors to consider are:

(i.) Width of existing overhead protection: This width includes the width of barricaded areas, as well as, the width of a narrow roof (when applicable) and if the roof is, in some cases, a potential landing area, with possibility of rebounding off the roof down to the ground.

(ii.) Adequate resistance to impact of the overhead protection with respect to the overall height of the panel section considered (review plywood thickness, use of steel, and other protective measures).

(iii.) Potential for presence of pedestrians (e.g. on sidewalks, uncovered bus station, and other areas where pedestrians may be present) in proximity to the overhead protection zones. To estimate the rating value, consideration is given to the width of the overhead protection (WOP) and to the area of public use (A), that may be uncovered and thus at possible risk. The expression of this rating will be function of a three main factors: (1) frequency of public presence in uncovered area; (2) overhead protection width, and; (3) position and surface area of uncovered region. More details about this calculation will be provided in Annex C.

(iv.) Potential for the presence of commuters (buses, cars). Equation 1 can be used with a lower weight, given that the type of harmful effect is assumed to be different (primarily material loss).

Table 8 – Assessment of consequence arising from occurrence of a harmful event
(Table shown illustrates values required for factor identified – not yet complete)

Consequence factors	Initial rating	Individual exposure area	Relative cost	Rating (rating × weights)
Pedestrians exposed	0.055	1	1	0.055
Vehicles exposed	0.025	95[18]	0.001[19]	0.002
Strength adequacy of overhead protection	Not yet implemented			
Sum				0.058
Qualitative scaling[20]				4

Since the level of uncertainty of the consequences is lower than the level of the likelihood, it is natural to adopt a higher scale for the consequences (2, 4, 6 versus 1, 2 and 3 for the likelihood). This way, on average, greater weight is given to consequence than likelihood.

Factoring the two risk components separately provides for the possibility of representing them on a risk grid or risk graph; an example of which is shown in Figure 34.

Otherwise by combining the likelihood of occurrence of an event and the consequence arising from the event, a risk ranking can be established for each section identified and for each elevation using the risk equation:

Risk = Likelihood × Consequence **Equation 2**

An example of risk rating between two Iso-risk sections and related calculations is provided in Appendix D.

5.3 Recommendations for risk mitigation measures

The table formats described in the previous section can be populated with the values of different factors (and potentially adjusted) to the best of the team's knowledge and drawing upon more in-depth knowledge when such information becomes available either from laboratory studies, or from a monitoring program, while keeping in mind that the risk assessment is an ongoing process that needs to be updated on regular basis and when any of the contributing factors are activated or new ones generated.

The risk ranking process described above can be achieved through current planned site visits and a series of targeted inspections. Until the building envelope gets replaced, available funds would allow targeting the brick facades with high-risk of failure with a course of action that minimizes either the likelihood of occurrence or the consequence of the resulting event. As shown in Figure 34, the overall risk (value = 15) can be reduced by reductions of either the severity or likelihood of occurrence of hazards. Additional or improved overhead protection diminishes severity from 3 to 1).

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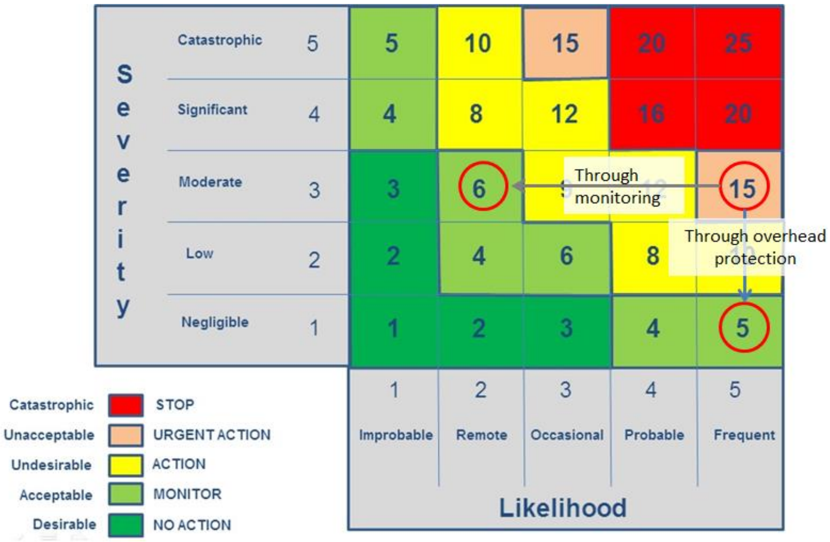
[18] Ratio of surface area of average car dimension to average surface area/person: details included in Appendix X

[19] Life cost vs. material damage cost: details to be included in Appendix X

[20] See Table 10 in Appendix D.2

Based on the actual state-of-knowledge, some recommendations for risk mitigation measures are proposed; recommendations in respect to overhead protection and façade monitoring and inspection are provided in Chapter 6 as relates to alternative facade maintenance-preservation options.



Severity		1 Improbable	2 Remote	3 Occasional	4 Probable	5 Frequent
Catastrophic	5	5	10	15	20	25
Significant	4	4	8	12	16	20
Moderate	3	3	6	9	12	15
Low	2	2	4	6	8	10
Negligible	1	1	2	3	4	5

Likelihood

Through monitoring

Through overhead protection

Catastrophic	🟥	STOP
Unacceptable	🟧	URGENT ACTION
Undesirable	🟨	ACTION
Acceptable	🟩	MONITOR
Desirable	🟩	NO ACTION

Figure 34 – Example of qualitative risk grid and examples of actions considered to mitigate identified risk factor and permit moving to lower risk level

6. Proposed alternative facade maintenance-preservation options with related costing (Task 3)[21]

On the basis of results derived from Tasks 1 and 2, a number of facade maintenance-preservation options are to be provided in this section together with related costing; the options are first described and thereafter the costing of each option is given together with a notional scheduling of activities.

6.1. Description of envelope preservation options

- Envelope preservation options for maintaining the integrity of the panels (i.e. as obtained from Task 1) and establishing typical construction and maintenance schedules over the expected remaining life of the envelope, as estimated in Task 2 are to be identified and described in this section, details of which are to be provided in a final report.
- What might be anticipated as forming part of an envelope preservation option is a monitoring program that would permit estimating the rate of failure of bricks on panels over a yearly cycle; a notional approach is provided in the subsequent section on monitoring.

Notional monitoring program ─ A monitoring program based on the steps presented below can further mitigate the ultimate risk from falling bricks; a more detailed program is to be described in the final report.

- Identify the location of brick deterioration by undertaking inspections, and monitor the brick face for damages throughout the remaining life of the façade;
- Repeated inspections permit determining the rate of deterioration of brick damage, and further confirm diagnosis for failure;
- During inspections, be aware of instances where "several bricks splitting parallel to the facade", as the affected areas might come loose and fall from the face of the panel. If encountered, look for visual signs such as continuous crack in mortar.
- Limit the repair to the removal of loosened bricks and replacement with a proxy component.
- To prevent further deterioration, consideration ought also to be given to weatherproofing exposed area utilizing materials other than masonry (e.g. use of spray PUR foam as temporary measure); such measures nevertheless need to be carefully studied to ensure these do not generate new risks.
- Propose more efficient methods for remediation (perhaps inspection twice annually in April and September;
- Propose alternate methods for inspection that will reduce cost of inspection or provide more useful information that will increase the reliability of information on the condition state of brick façade.

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[21] This Chapter is not yet complete; only an outline is provided in this report; it will be complete in the Final report

Overhead protection ─ Based on the proposed risk model presented in Chapter 5.2, and the mitigation measure suggested in Chapter 5.3, all landing areas (sections) are to be investigated. Results from ranking the respective risks will provide information necessary for:

- The addition of new overhead protection to provide additional cover over other potential landing areas adjacent to the facades and designed according to the height of the building; this addition may be minimal given the extensive area of the existing overhead protection at LTDLC.
- Assessing the adequacy of existing overhead protection; this measure may have been partially implemented by previous consultants.
- Investigating the possibility for the installation of shock absorbers on top of the overhead protection (e.g. soil- or sand- based products, retaining net/mesh or other suitable measures) where it is needed, to minimize the risk to the public from bricks or brick fragments that might rebound upon impact with the overhead protection. This measure can as well be implemented on low roofs beneath vertical walls immediately adjacent to windows where the risk of glass breakage from brick fragments also exists.

The recommendations provided below will require a more in-depth analysis;

- Consideration ought to be given to whether available funds be spent on improving the overhead protection rather than investing in brick repairs. Any investment in the repairing the brick masonry panels other than monitoring the deterioration rate and trying to identify sources of hazards (including very minimal repairs) would not likely be as efficient as compared to a thorough program of inspection for the reasons provided below:
    - Brick repair activities perhaps may lead, in some instances, to an accelerated rate of deterioration;
    - Considering any of the remediation options, the benefits of overhead protection investment vastly outweighs investing in brick repairs;
    - Suggest focusing on advanced inspection and monitoring program of damaged locations and reduce the repair activities to a minimum.

6.2 Costing of envelope preservation options

- Typical costs are to be identified in relation to the respective options and as might be incurred during the anticipated remaining life of the LTDLC wall panels, including cost levels and frequency; historical data from PSPC is required to complete this task.
- Estimating the overall costs for each of the envelope preservation option will be identified for which details will be provided in a final report.

6.3 Scheduling of envelope preservation options

- Developing notional schedules of activities in relation to the respective envelope preservation options on the basis of estimating the time to complete tasks will be prepared in this section and for which details will be provided in a final report.

7. Summary of findings and recommendations

The report has been advanced to the point where some recommended actions can be offered bearing in mind that the results of work to date are preliminary and certain recommendations are likely to be revised given the results of new work will necessarily be taken into consideration in a final report.

Preceding the overview on recommendations, a brief summary is given of findings resulting from project work to date; these findings will be updated once the project tasks are more advanced and new information is acquired.

7.1 Summary of findings

Despite the detailed observations of brick failures reported from previous inspections, the underlying causes of the premature deterioration of the brick panel walls had not been established. This step is a prerequisite for understanding the pathology such that a sound assessment of the deterioration rates and risks can be made and from which cost-effective facade maintenance solutions can be proposed to PSPC.

Cleary the results from the current project on review of the work and analysis of the information in the reports indicate that the wall panel system conceived in 1970s' for the TDLC project was then perhaps considered advanced, somewhat novel, but the design unfortunately was flawed from the outset. The fabrication of a precast masonry façade affixed to a concrete panel through shear connectors was perhaps not an unusual approach considering that methods for precast masonry were reasonably well developed by the mid70's. However, the choice of brick unit, and the use of a high strength, self-leveling mortar (perhaps a grout) with a greatly differing coefficient of thermal expansion as compared to the brick and that encased the units to form the exterior cladding is, based our current level of understanding, the primary cause of wide-spread failure of brick units. The failure of brick units was evident from observations described in several reports, from on-site inspection, and the mechanism of failure having been described in more detail through interpretation of our modelling results in context of the documented failures. As such, is this façade system nonetheless serviceable?

The brick veneer wall panel system will require continuous monitoring and perhaps repair for the remainder of its service life; it may indeed have already reached its end of life. As such it will continue to be a burden on PSPC resources, and pose a continual risk, whilst not providing the level of performance as was originally intended in its design. The courtyard will not yet be accessible, the overhead protection will still be required and risks to injury will nonetheless be present until such time as the envelope is replaced in its entirely.

In the final report, the following tasks will be concluded:

(1) Technical review of documentation and inspection of wall panels (Task 1a)

To complete this sub-task is a review of inspection information that was in the JCAL 2000 report is to be provided; this will nominally permit estimating the rate at which the brick units are failing.

(2) Numerical modelling and analysis of bricks and wall panels (Task 1b)

Several other numerical analyses are planned, the results of which will permit confirming existing observations and that will provide a better understanding of the deterioration mechanisms acting on the brick wall panels; this would include:

- A more accurate representation of stress development and crack formation in the brick wall by conducting a structural nonlinear analysis on the 2D single-brick and brick-wall models in which the effects of creep and cracking would be considered.
- Numerical analyses will also include hygrothermal and heat transfer effects on the entire wall assembly. Numerical models of will also be completed to study other possible damage mechanisms such as freeze-thaw action following moisture uptake by the brick and mortar.
- In addition to the thermal effects, the adverse effects of corrosion (volume expansion) of the reinforcing bars embedded in the cores of the brick units will be analyzed.
- To confirm the bowing of the panel and its severity due to differential drying shrinkage a 3D model of the concrete backing is to be completed.

(3) Results of in-laboratory inspection of a wall panel & laboratory testing of wall components (Task 1c)

There are a number of tasks that have not yet been completed and are to be reported in the final report; these include:

- Identification of steel reinforcing bars in the concrete panel and their corrosion condition
- Results from testing of brick units and brick panels
- Results from assessing basic properties and durability features of concrete panel
- Results from testing mortar and structural brick assembly including results from the uni-directional freeze-thaw resistance of a brick panel

The results of all of these tests will be considered in respect to their influence on the durability of, and the primary mechanisms of deterioration acting on the brick panels.

(4) Risk management of falling bricks from building facades (Task 2)

A proposal has been described in this report for risk management and within the framework for managing risks, such risks being based on assessing the likelihood for bricks to fall from facade panels together with an assessment of consequences arising from an occurrence of a harmful event.

Thereafter, recommendations for risk mitigation measures are to be provided as will a review of risks in relation to the existing overhead protection measures.

(5) Proposed alternative facade maintenance-preservation options with related costing (Task 3)

This section, currently in draft form, is to be completed in the final report and in which one will find descriptions of:

- Envelope preservation options;
- Inspection and monitoring program to further mitigate the ultimate risk from falling bricks and as well ensure the continued serviceability of the envelope
- Costing and notional scheduling of preservation options, taking into consideration any particular issues of importance to PSPC

7.2 Recommendations

The recommendations that can be made at this project stage include:

- Undertaking inspections of brick wall panels at least on an annual basis; the current mandate has biennial inspections; whether more frequent inspections ought to be completed would depend on the possible benefits that would accrue from obtaining additional information at an earlier stage; it is not immediately apparent if this is beneficial but this will be considered in the final report

- Estimating, on the basis of inspection results (currently being collected):
    - Rate of deterioration & remaining life of brick façade
    - Risks and change in risk associated with changes in rate of deterioration
    - Cost of repair or other interventions
- Determining the extent of repair, or other interventions, required to maintain reliability (level of acceptable risk) of the brick façade.
    - Given that it has been previously suggested that failed brick units need not be replaced, consideration should be given to determining whether openings in the brick façade is a near term risk issue; this will be dealt with in the final report
- Repairing the envelope air barrier if found defective
    - Undertake air leakage assessment to locate most vulnerable locations in envelope
    - Inspecting locations where air leakage is apparent.

APPENDIX A

Project Proposal

Regarding

Les Terrasses de la Chaudière (TDLC): Preliminary Risk Assessment of Existing Brick-faced Wall Panels

NOTICE

Restriction on Disclosure

Information contained in this project proposal document may not be disclosed, duplicated or used in whole or in part for any purpose other than in evaluation by PSPC. In the event that this document does not lead to a funded project, it must be returned to NRC upon written request. This restriction does not limit the use of information contained in the document if it is obtained from another source without restriction.

Introduction

The National Research Council Canada (NRC) is pleased to submit the proceeding Project Proposal (PP) document to PSPC. The following document shall be considered NRC's formal proposal pertaining to ***Les Terrasses de la Chaudière (TDLC): Preliminary Risk Assessment of Existing Brick-faced Wall Panels***, and is based on all available information provided by PSPC to NRC as of 29 February 2016. Should the scope of the current project change, or should additional information be provided to NRC that alters NRC's proposed work plan and/or proposed budget, NRC reserves the right to modify the proceeding document prior to acceptance by both parties.

Background

Les Terrasses de la Chaudière (TDLC) complex was designed by Arcop Associates and built by the Campeau Corporation between 1976 and 1978. The complex is composed of four office towers located in downtown Gatineau, between Promenade du Portage, Eddy, Wellington and Montcalm streets. On the West side, the complex is bordered by Delta Hotel, but the hotel and its parking garage are excluded from this project. The four towers are 7, 19, 19 and 28 stories high and are linked at their first and second levels by a retail concourse and the basement levels by a tunnel system. The total rentable floor area is 142,353 m^2, accommodating over 6,000 people, as well as retail and storage space. It is the single largest federal office complex in Canada, containing the administrative headquarters of Environment Canada, Aboriginal Affairs and Northern Development Canada, Canadian Heritage, the Canadian Radio and Telecommunications Commission, and the Canadian Transportation Agency.

The four precast towers are reinforced concrete structures, covered with prefabricated, brick-faced panels that form most of the building envelope. Below the second floor, the exterior walls consist of brick-veneer over a concrete back-up wall with aluminum-framed windows and doors. The corner (bay) sections are comprised of a curtain-wall assembly, with insulated clad spandrel panels. The exterior wall was designed as a drained system, using the airspace between the brick and insulated back-up wall as the drainage cavity. The exterior envelope of the lower two building levels forming the pedestrian concourse is of conventional masonry, rather than prefabricated systems.

Since the construction of the complex, the exterior brick-cladding has undergone advanced deterioration, presently creating potentially serious health and safety issues. A brick inspection and repair program is underway to maintain safety standards, but a permanent solution is needed to rehabilitate the full building envelope system, including windows, curtain wall, mechanical/electrical interface, and interior finishes. It is anticipated that the exterior building envelope will be implemented in at least two phases, so that the tower exterior envelopes will be rehabilitated first, followed by rehabilitation of the lower two levels forming the podium and the ground level circulation systems.

PSPC is engaging a consultant to develop schematic designs (incl. seismic upgrades) and construction implementation strategies to rehabilitate the TDLC complex building envelope to address health and safety issues, as described in the Building Envelope Retrofit Feasibility Study (Smith Carter 2013).

The work of the consultant will entail a detailed review of all available documentation and reports; analysis of the as-built conditions; review of the options for the exterior building envelope and seismic resistance; development of four design options as well as a recommended option; construction implementation strategy, and presentations to authorities with jurisdiction.

NRC Commitment to Project

NRC fully understands the importance of this project for PSPC as it represents a very high profile re-cladding initiative which when completed may be the largest ever in North America. NRC is committed for this initial service engagement and throughout the lifecycle of the project to provide its expertise where applicable to ensure that this project is a success and becomes a showcase project for PSPC.

Objectives

NRC has been asked to provide technical support to PSPC on the following tasks:

(1) Technical review of reports and data sets provided by PSPC related to the condition of the brick-faced wall panels.
(2) Overall risk assessment of observed deterioration of brick wall panels.
(3) Provide alternative facade maintenance-preservation options with related costing.

Work Plan

Task 1 – Technical Review of Documentation and Inspection of Wall Panels

NRC will:

1. (1) Collect all pertinent information and data that are available, in order to conduct an overall risk assessment of the different TDLC buildings and facades (Re: Task 2).
2. (2) Review the provided documentation and available data sets and identify areas where missing data and clarifications are required from PSPC or their consultant. Such data will be needed to initiate Tasks 2 and 3.
3. (3) Follow the in-laboratory inspection of a wall panel specimen (to be delivered to NRC labs), further appraise the pathology of the bricked-faced wall panel deterioration; provide options for repairing and preserving the integrity of the panels.
4. (4) Undertake additional on-site inspections as may be required to further understand the pathology of the bricked-faced wall panel deterioration.
5. (5) Analysis and review of the options analysis provided by John Cooke Engineering in their most recent Brick Inspection Report including observations on current approach of brick inspection and repair not sustainable past 2020

Task 2 –Overall risk assessment of brick-faced wall panels

NRC will conduct a number of tasks to complete the Risk assessment (RA) of TDLC brick-faced wall panels. The risk assessment concept will be based on the combination of the three components: *Sources of hazard, vulnerability of the envelope and consequence of failure*.

<u>1 – Source(s) of hazard:</u>

On the basis of information provided in the various engineering reports, and any in-situ or in-laboratory inspection of wall panels, the following sub-task will be conducted:

- Identify the major factors leading to brick failure of TDLC bricked-faced wall panels.
- Identify other factors, and apart from those affecting the brick facia, that have led to deterioration of other panel components and that affect the serviceability of the wall panel (e.g. water leakage and moisture uptake; lack of or missing insulation).
- Assess prevalent environmental loads acting on the bricked-faced wall panels at the TDLC complex location and from this classify the likelihood of causal effects on the different faces of the respective building facades (i.e. the extent to which, direction, height and severity of load affect the risk to premature failure of panels).

<u>2- Vulnerability assessment of the TLDC envelope</u>

The vulnerability is mainly related to the physical condition of the TLDC. Based on the data available from previous reports and the information from Task 1, estimate the overall condition state of bricks (e.g. characteristic material properties; corrosion rate; brick spalling rate) and likewise the condition state of the brick-panel system; it may be possible to estimate the remaining service life of the panels based on information developed in this section.

Following which, and if possible, a comparison is to be made between the estimated rate of brick failure up to end of the remaining life to that of traditionally constructed brick facades located at the TDLC site, and as might be found on the lower floor of the TDLC complex.

NRC will also seek the support of the consultant that undertook the surveys such that the failure data can be readily parsed and made useful to informing on the vulnerability assessment.

3- Consequence of failure event

The failure event in this context is defined as "falling brick(s)". Depending on the mitigation measures in place (overhead protection, regularity of inspections, etc.) or that might be proposed, the severity of the consequence might vary from one building to another or from one facade to another (e.g. presence of window sill or not). This would directly affect the overall risk incurred by vehicles or pedestrians in proximity to the building. This information, in turn, would allow developing a simplified risk model to estimate the overall risk of failure and from which a risk rating of different buildings and/or facades can be established. This information would be useful in developing refurbishment scenarios that minimise the risk rating when undertaking maintenance and refurbishment activities over the course of the remaining life of the envelope.

Task 3 – Provide alternative facade maintenance-preservation options with related costing

NRC will conduct the following tasks to complete costing of alternate envelope preservation options. Such tasks will include:

- Identifying the typical costs as might be incurred during the anticipated remaining life of the TDLC wall panels, including their cost levels and frequency; historical data from PSPC is required to complete this task.
- Identifying envelope preservation options for maintaining the integrity of the panels (i.e. as obtained from Task 1) and establishing typical construction and maintenance schedules over the expected remaining life of the envelope, as estimated in Task 2.
- Estimating the overall costs for each of the envelope preservation options identified.

Deliverables

Task 1 – Technical Review

NRC will early on in the project provide PSPC with a list of items required to permit completion of the Tasks 2 and 3 of the project, indicate where clarifications are needed and highlight areas of concern; the requirement for a panel to be delivered to NRC laboratories is a prerequisite for initiating Tasks 2 and 3; likewise this is to be completed no later than 7 April, 2016.

NRC will prepare a draft report by 6 May, 2016.

Tasks 2 and 3 – Overall risk assessment and maintenance-preservation options & costing exercise

NRC will deliver an updated draft report on findings of Tasks 2 and 3 as of 7 June, 2016; a FINAL report including the work description, data, analysis and conclusions pertaining to the 3 major tasks identified above will be provided at a later date, but no later than 30 July, 2016.

Responsibilities

PSPC will be responsible for providing the following items:

- Provide all pertinent reports for review (for Task 1);
- Any background documents deemed necessary to complete the proposed project (for Task 1);
- Any inspection or survey data or data of tests conducted on the brick and mortar materials of the TDLC envelope (for Task 2);
- Any historical cost details on unit costs of typical materials and typical repairs (for Task 3).
- PSPC will provide access to the site and swing stage operation to permit survey of the wall panels as required by NRC;
- A wall panel specimen delivered to the NRC laboratories no later than 7 April 2016; any delays beyond this will likely affect project outputs of all Tasks.

NRC-Construction's immediate responsibilities relate to the above mentioned deliverables.

Proposed Budget

The costs for each task are provided in the table below.

Work Task Description	Total (CDN$)
Task 1 – Technical Review	$52,680
Task 2 – Overall Risk Assessment	$74,260
Task 3 – Maintenance-preservation options with related costing	$23,060
TOTAL (without applicable taxes)	**$150,000**

Project Plan/Schedule

Assuming a start date of 18th April 2016, the following schedule is proposed.

Task	April	May	June	July	Aug.	Sept.	Oct.	Nov.
1 – Technical Review	🟧	🟧	🟧	🟧	🟧			
(**I** :Interim; **F:** Final) Reports			**I**		**F**			
2 – Service Life Estimation	🟦	🟦	🟦	🟦	🟦	🟦		
(**I** :Interim; **F:** Final) Reports			**I**				**F**	
3 – Life Cycle Cost Analysis				🟪	🟪	🟪	🟪	
Results from A1-007922		🟩	🟩					
(**I** :Interim; **F:** Final) Reports			**I**					**F**

Tasks	Duration	Deadline	Deliverable*
1 – Technical Review	~4 months	29 August, 2016	1st Draft report
2 – Service Life Estimation	6 months	10 October, 2016	Updated draft report
3 – Life Cycle Cost Analysis	4 months	6 November, 2016	Final report

* A draft of each of these sections will be provided prior to 8 June, 2016.

Project Team

The project manager will be Dr. Michael Lacasse, with support from Mr. Mark Arnott, Dr. Daniel Cusson, Dr. Bassem Saassouh, Mr. Ken Trischuk and Dr. Jieying Zhang of the Civil Engineering Infrastructure Group and Dr. Carson Banister and Mr. Steve Cornick of the Heat and Moisture performance of the Building Envelope Group. Other staff may be consulted as required.

The consultant with whom PSPC worked on the survey of the wall panel deterioration is sought as support to NRC

Project Risks

The project is under an extremely tight deadline to deliver reports and useful information to PSPC. Consequently, NRC is seeking a highly cooperative and close liaison with PSPC to help ensure a responsive exchange of information such that deadlines for deliverables can be met.

Emphasis is also placed on having PSPC provide a specimen of the wall panel in a timely manner without which progress cannot be made on subsequent tasks.

DISCLAMER: NRC will rely in good faith on the information provided by PSPC and their consultants and does not accept responsibility for any deficiencies or inaccuracies from the proposed work as a result of omissions or misinterpretations of others. NRC offers no warranty, expressed or implied that the proposed work will uncover all potential deficiencies and risks of liabilities associated with the subject property. The recommendations that may be put forward in the final report will not constitute technical specifications for purposes of construction. They are intended to guide PSPC as to possible risk management strategies for the maintenance and preservation of the brick-faced wall panels.

APPENDIX B –
LIST OF DOCUMENTS PROVIDED BY PSPC

1.		Partial Architectural Drawing Set, entitled "Les Terrasses de la Chaudière – Campeau Corporation"; Arcop Associates; drawings A147, A162, A163, A167, A168 and A170.
2.	1976	Precast panel shop drawings (19 drawings) prepared by Beer Precast Concrete Ltd. (Adjelelian & Assoc. Consulting Engineers) 1976
3.		Report entitled, "Expertise d'Infiltration d'Eau – Les Terrasses de la Chaudière; prepared by **CABA** Inc.; December 1995
4.	1997	Report entitled, "Structural Expertise – Terrasses de la Chaudière, Block 300", Project No. : E-840-97; prepared by Consultants Andre Beaulieu & Associes (**CABA**) Inc. and dated April 1997
5.	1998	Report entitled, "Building Envelope and Structural Investigation – Les Terrasses de la Chaudière; prepared by **CABA** Inc. and Adjelelian, Allen, Rubeli Ltd. ; March 1998 (shows locations of deficiencies on buildings in elevation drawings)
6.	1999	Report entitled, "Les Terrasses de la Chaudière – Free Fall Brick Trajectory Testing Report", Project No. 00018; prepared by John G. Cooke & Associates Ltd. and dated October 1999
7.		Preliminary Report entitled, "Repairs to the Vertical Envelope of the Buildings of the Terrasses de la Chaudière Office Complex", prepared by Consultants Andre Beaulieu & Associes Inc. (**CABA**) and date-stamped November 1999 (as translated by PWGSC)
8.	2000	Report entitled, "Structural Evaluation Report of Terrasses de la Chaudière Brick Condition Inspection", prepared by John G. Cooke & Associates Ltd. and dated December 2000
9.	2001	Report entitled, "Second Opinion Review of Investigation and Remedial Plans for Les Terrasses de la Chaudière", prepared by Morrison Hershfield; Report No. 200 2033.01; 23 April 2001
10.	2004	Report entitled, "Terrasses de la Chaudière – Brick Condition Inspection", Project 03062; prepared by John G. Cooke & Associates Limited; March 2004.
11.		Report entitled, "Historical report: Terrasses de la Chaudière"; prepared by Content works, June 2004
12.		Report entitled, "Terrasses de la Chaudière – ReCaPP Validation Survey – Condition Survey"; Zenix Engineering Ltd.; 31 March 2004
13.	2005	Report entitled, "Energy Management Report - Les Terrasses de la Chaudière, Gatineau, Quebec"; Jacques Whitford; May 27, 2005.
14.		Letter report entitled, "Terrasses de la Chaudière Building Complex – East Elevation of 10 Wellington", prepared by John G. Cooke & Associates Ltd. and dated June 9, 2005
15.	2006	Report entitled, "Building Condition Report – Les Terrasses de la Chaudière: 15 and 25 Eddy Street (DRAFT)", Zenix Engineering Ltd.; January 2006
16.		Report entitled, "Building Condition Report – Les Terrasses de la Chaudière: 10 Wellington St.", Zenix Engineering Ltd.; January 2006
17.		Report entitled, "Building Condition Report – Les Terrasses de la Chaudière: 1 Promenade", Zenix Engineering Ltd.; January 2006
18.	2010	Report entitled, "Terrasses de la Chaudière – Brick Facade Investigation", prepared by John G. Cooke & Associates Limited, dated February 2010.
19.	2011	Report entitled, "Terrasses de la Chaudière - Panel Anchor Investigation and report", prepared by Robertson Martin Architects Inc., February 2011
20.		Report entitled, "Seismic Assessment of Exterior Facade Anchorages"; Dessau; 7 April, 2011

21.		Report entitled, "Terrasses de la Chaudière - Structural Seismic Assessment of Building Blocks 100, 200 and 300; Tome 3 of Volume I (1 or 2) ; Ref. N°: 038-P037688-0120-SR-00; Dessau; 1 April, 2011
22.		Report entitled, "Terrasses de la Chaudière - Structural Seismic Assessment of Building Blocks 100, 200 and 300; Tome 3 of Volume I (2 of 2); Ref. N°: 038-P037688-0120-SR-00; Dessau; 1 April, 2011
23.		Report entitled, "Terrasses de la Chaudière - Structural analysis results of building – Block 100 (Tome 1 of Volume 2); Ref. N°: 003-P037688-0120-SR-00; Dessau; 11 March, 2011
24.		Report entitled, "Terrasses de la Chaudière Structural analysis results of building – Block 300 (Tome 3 of Volume 2); Ref. N°: 003-P037688-0120-SR-00; Dessau; 11 March, 2011
25.	2012	Letter Report entitled, "Split Brick Panel above Corner Bay Windows"; John G. Cooke & Associates Limited; October 1, 2012
26.		Report entitled, "Terrasses de la Chaudière – 2011 & 2012 Brick Repair", Construction Review Report No. 23; October 24, 2012
27.	2013	Report entitled, "les Terrasses de la Chaudière Gatineau, QC – Building Envelope Retrofit – Feasibility Study and Options Analysis; PWGSC Project No. 10C-00053-30; April 2013
28.		Excerpts of Report entitled, "Building Condition Report Les Terrasses de la Chaudière Hull; P401362B", prepared by Halsall Associates; April 2013
29.	2014	Letter report entitled, "Terrasses de la Chaudière Brick Inspection 2013/2014 Progress Report No. 4", prepared by John G. Cooke & Associates Ltd. and dated September 2014
30.		Letter report entitled, "Les Terrasses de la Chaudière Overhead Protection Impact Study", prepared by Adjeleian Allen Rubeli Limited; September 2014
31.	2015	Report entitled, "Les Terrasses de la Chaudière 2013/2014 Brick Facade Inspection Report", prepared by John G. Cooke & Associates Ltd. and dated January 2015
32.		Report entitled, "Assessment of Masonry Inspection and Repair Program / Overhead Protection Measures - Les Terrasses de la Chaudière"; Patenaude Trempe Van Dalen Inc. (PTVD); Project No. O-0236-A; January 2015
33.		Report entitled, "Les Terrasses de la Chaudière Building Envelope Rehabilitation – Options Analysis Update"; GRC Architects; PWGSC Project No. R.068114.320; 23 October, 2015
34.	2016	Report entitled, "Les Terrasses de la Chaudière Building Envelope Rehabilitation - Schematic Design Report"; GRC Architects; PWGSC Project No. R.068114.320; 26 February, 2016

APPENDIX C –

PROBABILITY FUNCTIONS OF DISTANCES FROM BUILDINGS FACADES SHOULD BRICK UNITS FALL

C.1: Modelling the possible landing areas with respect to buildings heights

Based on the information provided in the report, it was mentioned that brick fragment could reach a distance of 30 m from the façade of the building. This distance represents approximately 1/3 of the height of the building. In order to model a probability density function for brick landing areas, the assumptions below were used:

- A falling brick bouncing on a window sill or other component could reach a distance of 1/3 of the height of the building (H). More accurate values regarding this assumption can be verified through some lab testing and analysis.
- Since it is more likely to land closer to the building façade in all the cases when no bouncing is present, we considered a quadratic function (parabola) rather than linear function.
- The vertex of the parabola is taken as the last possible landing point.
- For any considered section, the frequency of possible landing depends only on the distance from the section and assumed to be constant throughout the width of the section (dimension perpendicular the plane of the figure below). Therefore, it can be represented using a 2D model as in Figure 35.

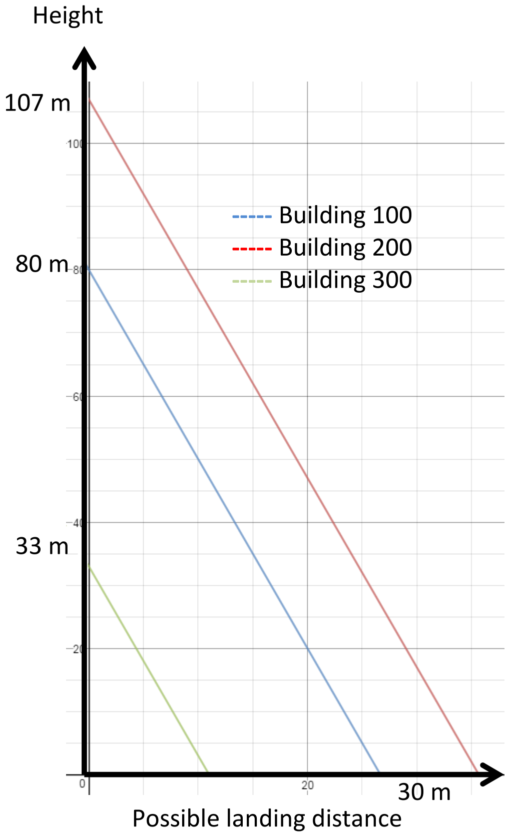

Figure 35 – Height with respect to possible brick landing distance

The parametric function modelling the curves in the figure becomes:

$$y = f(x) = -3x + H \qquad \textbf{Equation 3}$$

f(x) will be used to model the probability density function p(x) of possible landing areas.

In addition, it is assumed that there is no risk to the public anywhere in the barricaded areas or underneath the overhead protection. The shaded area in blue in Figure 36 represents that risk factor. The distance D represents the distance of uncovered area where pedestrians might be exposed

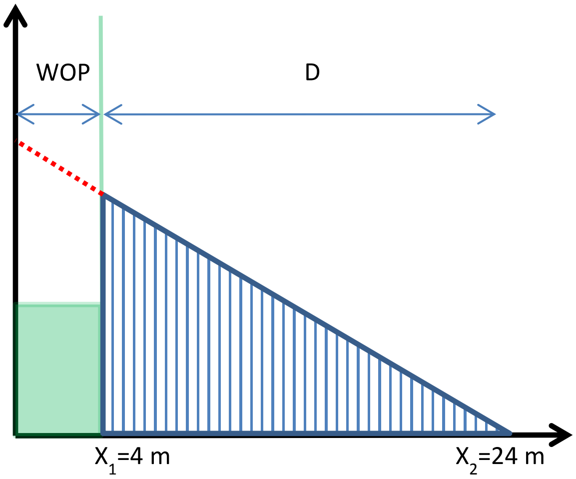

Figure 36 –Brick landing distance considering width of overhead protection

C.2: Probability density function

The probability density function that represents the possible landing areas can be written as follows:

$$p(x) = (-3x + H)\left(\frac{6}{H^2}\right) = -{}^{18}\!/_{H^2}\, x + {}^{6}\!/_{H} \qquad \textbf{Equation 4}$$

Figure 37 shows the probability density function of possible landing areas.

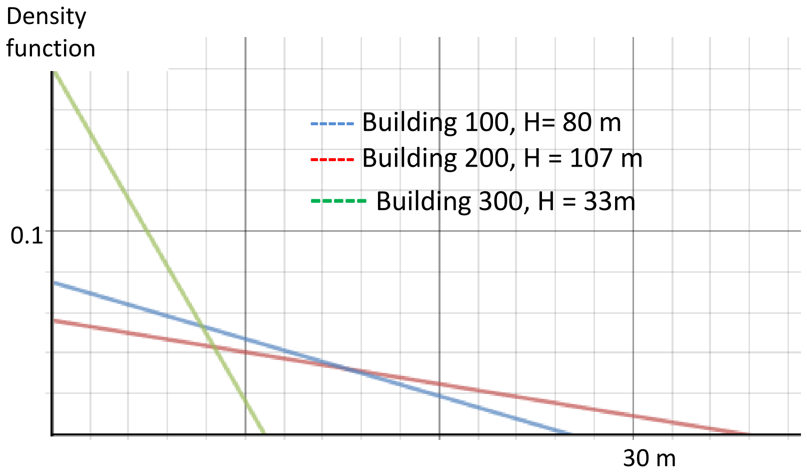

Figure 37 –Probability density function of landing areas

C.3: Consequence to pedestrian rating

This rating can be seen as consequence assessment. In other words, assuming a brick falling event taking place, severity of the consequence depends mainly on pedestrian exposure areas and frequency.

In case the frequency of pedestrians can be given as function of the distance x from the building $F_i(x)$, this rating can be written as:

$$R = \sum_i \int_{x_1}^{x_1+Di} p(x).F_i(x)\,dx \qquad \textbf{Equation 5}$$

where i represents the different type of exposure, for example during the week days vs. weekends.

As a practical approximation, the average daily frequency can be estimated in the exposure area. Therefore, $F_i(x)$ is considered as constant and the rating can be written as:

$$R = \sum_i F_i \int_{x_1}^{x_1+Di} p(x)dx \qquad \textbf{Equation 6}$$

Keeping in mind that the frequency is given by unit width of the section considered (See example in Appendix D for more details).

If the average frequency beneath the same section varies significantly with that of the Iso-risk section (e.g. bus station versus vs. sidewalk), it would be preferable to re-visit the initial step in the implementation of the model which is where the Iso-risk sections are defined. In other words, the width of a bus station with a minimum cover, suggests an updated sectioning of the façade in order to take into consideration the discrepancy in risks in the same section.

APPENDIX D –

EXAMPLE OF RISK RATING BETWEEN TWO ISO-RISK SECTIONS

D.1: Introduction

The example below shows a use-case of the model proposed. The first step of the model which is the Iso-risk sectioning is assumed to be completed in an earlier stage. The objective is to present a comparison between the two sections delimited by the red lines.

In this section an example of risk rating of the different risk factors mentioned in chap. 3 are presented. The calculation will allow having a total likelihood rating of a brick falling from any of these two sections and a total consequence rating for each of them.

The idea is to be able to compare the risk rating of these two sections (Figure 38 and Figure 39) and to have the ability to act, through reducing any of the risk factors, on one or the other in order to reduce its associated risk if deemed necessary.

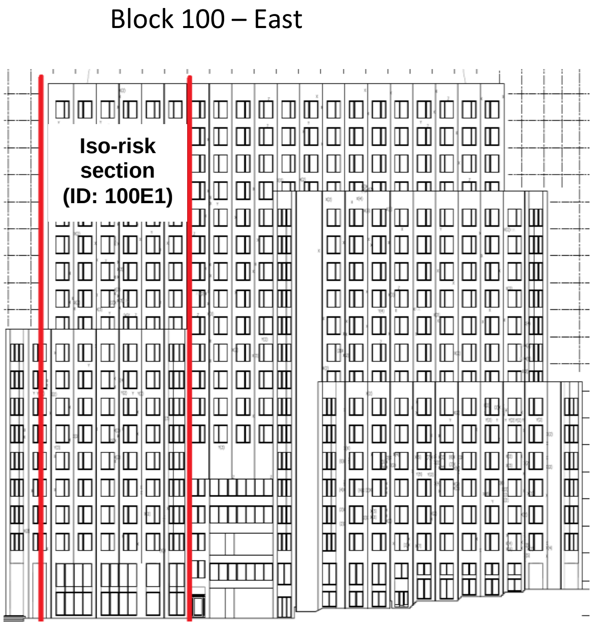

Figure 38 - Block 100 Section above the bus station

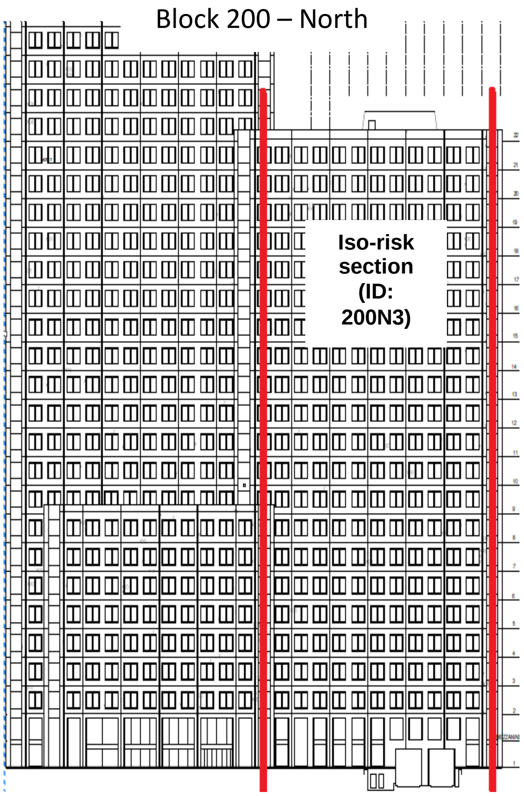

Figure 39 - Block 200 section above the loading docks

The example is incomplete in the sense that the calibration of the different factors, such as their normalization and their weighing factors needs adjustment based on upcoming finding and on expert judgment.

D.2: Consequence rating

Table 9 represents the different information needed to define the rating of each factor.

Table 9 - Information required for defining ratings for each factor

		Section 100E1 (Figure 38)			Section 200N3 (Figure 39)		
	Consequence factors	Metrics	Calculated value	Rating	Metrics	Calculated value	Rating
Consequence rating based on pedestrian and exposure	Height of the building	72 m	R1=0.056 (see section A below)	4	82 m	R2 = 0.036 (see section B below)	3
	depth of safe area	4 m			0 m		
	depth of exposed areas outside overhead	X_1 = 4m, X_2 = 72/3 = 24 m			X_1 = 0m, X_2 = 82/3 = 27.3 m		
	Average daily frequency of pedestrians	0.08 (see section A below)					
	Adequacy of overhead	NA[22]					

D.2.1. Section 100E1: Quantitative consequence rating based on frequency & area of exposure:

As a first approximation, the calculation is based on:

- The presence of 10 people present at a bus station for 2 hrs every 24 hrs
  (i.e., 1 hr in the AM and 1 hr in the PM);
- At this level, WEs are not considered differently;
- 2 people on average passing by all the time during the day time (e.g. over a 12 hr period).
- Height of the building H = 72 m
- Dimension of the exposed area is shown in Figure 40 (23 m x 24 m).

The equation below allows calculating the frequency of pedestrians in the area:

$$F = \frac{10\left(2/24\right) + 2\left(12/24\right)}{width = 23} = \frac{1.83}{23} = 0.08 \text{ person/hr/m}$$

This frequency is to be combined with the probability density function, *p(x)*, of possible landing areas.

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[22] NA: Not yet available

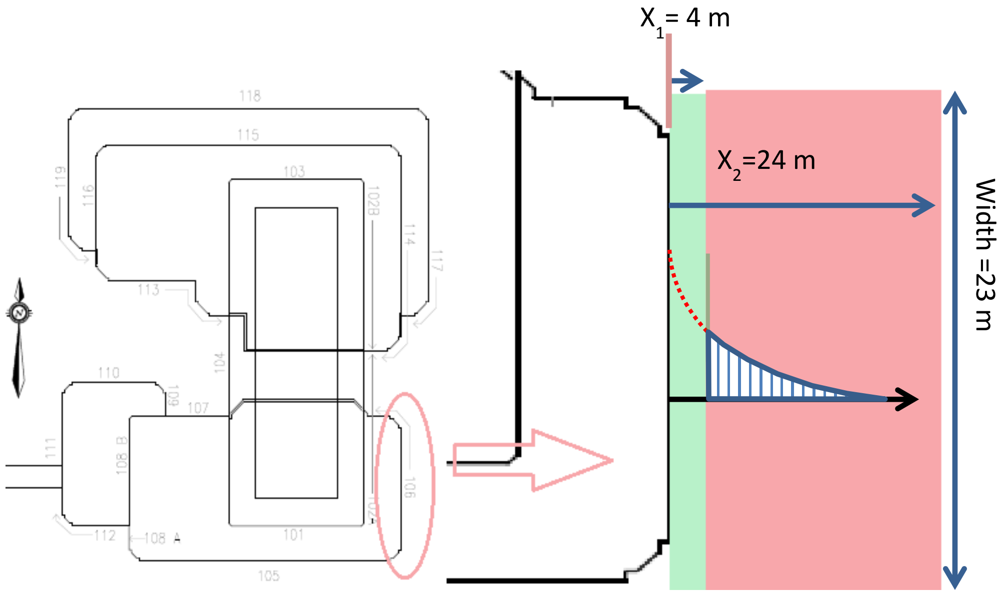

Figure 40 - Example of Size and Location of exposed area (section 100E1)

The probability density function, *p(x)*, can be written as:

$$p(x) = -\frac{18}{H^2}x + \frac{6}{H} = -0.00347x + 0.0833$$

Therefore, R_1 can be calculated as:

$$R_1 = F\int_{x_1=4}^{H/3} p(x)dx = F.\left(\frac{9}{H^2}x_1^2 - \frac{6}{H}x_1 + 1\right) = 0.08.(0.694) = 0.056$$

D.2.2. Section 200N3: Quantitative consequence rating based on frequency and area of exposure

Similar to the calculation completed for section 100E1, the current available information and assumptions are:

- The presence of 5 workers at the loading docks for 3 hours and for 2 days / week
- WEs are not considered as different at this level
- 2 people on average passing by during the day (12 hours).
- Height of the building H = 82 m
- Dimension of the exposed area is assumed to be 33 m x 27.3 m as shown in Figure 41.

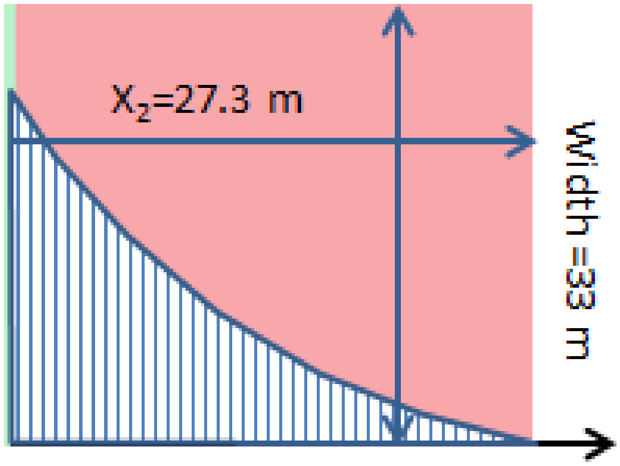

Figure 41 - Example of Size and Location of exposed area (Section 200N3)

The equation below allows calculating the frequency of pedestrians in the area:

$$F = \frac{5\left(\frac{6}{7(24)}\right) + 2\left(\frac{12}{24}\right)}{width = 33} = \frac{1.17}{33} = 0.036 \text{ person/hr/m}$$

This frequency is to be combined with the probability density function *p(x)* of possible landing areas, where *p(x)* can be written as:

$$p(x) = -\frac{18}{H^2}x + \frac{6}{H} = -0.00268x + 0.0732$$

Therefore, R_1 can be calculated as:

$$R_2 = F\int_{x_1=0}^{H/3} p(x)dx = F.\left(\frac{9}{H^2}x_1^2 - \frac{6}{H}x_1 + 1\right) = 0.036.(1) = 0.036$$

D.2.3. Calibration and normalization

To calibrate the rating for the consequence, we consider linear model taking into account the worst case and best case scenarios that could be present:

Worst case Scenario:

- The existence of a bus station with the frequency mentioned in the example
- No overhead (all area is exposed)
- Narrowest section: which is similar to the 2nd case considered in addition to removing the effects of overhead protection.

This would lead to: $R_{worst} = 0.08$

Best case scenario:

- Average existing people (2 people/12hrs)
- without bus station, nor rush hours nor loading zones workers
- Block 300 (shortest: $H = 3.718 * 8 + 5.272 = 35m$))

- Existence of 4 meters overhead protection
- Widest section of Block 300 (w = 10.(6.069)=60.69 m)

This would lead to: $F = \frac{2\left(12/24\right)}{w} = \frac{1}{60.69} = 0.016 \text{ person/hr/m}$

$$R_{best} = F\int_{x_1=4}^{H/3} p(x)dx = F.\left(9/H^2\, x_1^2 - 6/H\ \ x_1 + 1\right) = 0.016.(0.431) = 0.0071$$

Qualitative scale:

Step = (0.08-0.0071)/5 = 0.015

Table 10 – Scale for consequence rating

Pedestrian exposure	< 0.02	0.02-0.035	0.036-0.050	0.051-0.065	> 0.066
Qualitative Scaling	1	2	3	4	5

D.3: Likelihood rating

In this section, an example of the likelihood rating of a brick to fall is presented. The example does not integrate yet all the information from the different reports; especially qualitative and/or incomplete data where an extra effort is needed in order to collect pertinent data, map them into a qualitative scale and normalize them with respect to the other likelihood factors.

From the JCAL 2015 report, an estimation of likelihood rating can be completed and thereafter tabulated as provided in Table 11:

The three likelihood factors considered for this example are as-follows:

- Number of damaged bricks per panel width: In order to calculate this value, the number of damage in the specified section is calculated than divided by section width and by the duration between inspection
- Percentage of "damaged brick with possibility of rebounding" (Type Z and at window edges)
- Overall section condition: In the meantime, this factor is estimated based on the ratio between numbers of panels presenting any type of damage vs. the total number of panels in that section. The estimation's accuracy of this factor would be enhanced whenever lab results and pathology investigation are completed.

The two sections previously considered are compared, from the point of view of: "likelihood of failure"; the information is provided in Table 11.

Table 11 - Likelihood assessment of two sections

		Section 100E1			**Section 200N3**		
	Likelihood factors	Section width	Calculated value	Rating	Section width	Calculated value	Rating
Likelihood rating based on 2015 inspection report	damaged bricks (2015)/section width/month	3x7.6= 22.8 m	137/22.8/ 57.5[1] = 0.1	2.5 TBC[2]	6x6.069 =36.4 m	95/36.4/57.5 = 0.05	1.25
	Percentage of damaged bricks with high risk of rebounding		63/137= 46%	2.5		44/95= 0.46	2.5
	Overall section deterioration condition		72 /102 = 70% % panels defected	3.5		42/120=35%	1.75
Total rating				**8.5[3]**			**5.5**

[1] 57.55: Number of months between the last two inspections

[2] Rating to be calibrated once reaching a clear idea of results for all sections; currently a value of 0.1 is considered as the average value which is 2.5

[3] Assuming all factors have the same weight value (see likelihood Assessment table)

D.4: Risk Grid and Risk rating

Results above can be represented on a risk graph as follows:

The risk rating can be obtained by combining the likelihood and consequence. This would give:

For Section 100E1: R = 34 vs. R = 16.5 for section 200N3.

The integration of various weighing factors may have an effect on this result. The values of those factors will be based on expert opinions and will be discussed, calibrated and integrated to the model, at a later stage.

APPENDIX E –

FURTHER OBSERVATIONS ON PATHOLOGY OF FAILURE OF BRICK-FACED CONCRETE PANELS

Some of the observations that are worth mentioning and can help in the identification of sources of deterioration are mentioned below:

- One way of pathology investigation could be the distinction between two aspects of brick failures: the common problems/defects in brick masonry, and the damages related to the uncommon system in place (reinforced prefabricated panels). Some of the common causes might be exacerbated by the particularity of the uncommon system in place.
- While identifying sources of damage, it is important to highlight the concept of multi-stressors combination, for example:
    - Localized freeze-thaw cycles aggravated by the presence of mortar in the cores of the bricks and the half-deteriorated mortar joint.
    - Thermal expansion of brick, mortar and/or steel reinforcement, which might lead to fatigue, especially in the presence of local deficiencies like air/moisture infiltration, which might further lead to uneven expansion.

Other factors could explain the non-consistency of brick damage rate revealed by inspections between 2009 and 2014 (e.g. decrease from 7883 to 3223 or from 106 bricks/month to 56 bricks/month) could be due to a rare climate event taking place before 2009 that affected the severely some critical bricks leading to the observed amounts of damage. For example, this could have been caused by:

- Rare climate events such as severe decrease or increase in temperature or prolonged periods of elevated temperature, freezing rain events, which could lead, for example, to excessive deformations in either the brick or mortar.
- Seismic events that may have induced some damage to the cladding system.
  Rapid fluctuations in temperature in combination with other effects could as well lead to non-synchronous expansions between components (brick, mortar) that in turn could result in fracture of the brick, as is shown in Figure 42.

Figure 42 – Example of brick failure on wall panel

Other observations related to previously reported inspections and repairs are presented below:

- Most of the brick masonry deterioration (> 87%) observed on the different panels were evident in proximity to the windows or at panel extremities (Figure 43). Whereas corrosion phenomena is not thought to be the primary source of deterioration of the brick masonry units, the panelised brick masonry system (with embedded steel reinforcing and grout) is considered an uncommon system and one that is likely the source of the failures so evident on the facades. It is expected that results from laboratory being completed on the brick and mortar components will shed insight into possible sources of these hazards.
- Another scenario that could explain brick damage at the window and at the edge of panels is the fact that these extremities are more exposed to wind driven rain, that create an uneven thermal expansion at the edges of the window, panels and lintels leading to a non-uniformly distributed stress at the edges (Figure 43). The steel reinforcement may aggravate this situation by increasing the stress on parts of the brick while retaining the other part.
- This step of risk assessment is critical since the data that is currently at hand and needed for modelling the rate of deterioration with respect to time is incomplete, mainly due to continual repair of the wall. No information is available from any crack growth study or deterioration monitoring.

  A well-defined inspection program, with the purpose of deterioration monitoring and diagnosis of local deficiencies would provide a better diagnosis of the causes of deterioration, and that can help validate some of the deterioration scenarios or reveal new ones. Those potential causes of deterioration, once identified, can be integrated into the risk model and may help in providing more accuracy to the risk rating proposed here.

Figure 43 – Examples of brick damage at panel edges and window

APPENDIX F –

REUSE OF BRICKS FROM THE EXISTING BUILDING FACADES IN A CONCRETE MIX

Les Terrasses de la Chaudière (LTDLC) Complex is planned to undergo a major $185M re-cladding project starting in 2017 over 5 years, consisting of replacing nearly 5000 precast brick wall panels. Finding ways to recycle the bricks that will be removed from the buildings is very important to the owner as it would permit compliance with LEED's program, and as well, it would potentially reduce or even avoid the cost of disposal of bricks to landfills. To this end, PSPC have contacted recycling organizations and to date, none of these has shown interest in these particular bricks, given that the bricks (potentially) have low strength and a large porosity, making them susceptible to freeze-thaw durability issues. This in fact will be further discussed in light of results from laboratory testing of the brick units.

NRC is proposing a recycling application be developed and validated in which the bricks would be crushed to a given size (e.g. maximum size 5 mm), and subsequently used as a porous fine aggregate to enhance the internal curing process in the high performance concrete. It has been shown at NRC that internal curing using a porous fine aggregate can provide concrete with significant benefits such as improving its cure, eliminating shrinkage and the related cracking, and thus resulting in a concrete having a prolonged service life with reduced maintenance cost. It appears that these bricks, once crushed, may be a suitable material for the internal curing of concrete. If proven to work, large quantities of recycled bricks may find an application in a number of important construction markets, such as bridge decks, concrete highways, and parking structures, for which PSPC manages some of these infrastructure assess.

The main tasks of the proposed project will include a feasibility study, followed by concrete mixture development and testing work, and concluded with a demonstration project, in which precast concrete slabs may be built for installation in the future LTDLC complex.

The following benefits to the client are foreseen:

- Demonstrated application for the recycling of the bricks from the LTDLC re-cladding project
- Ability to find partners interested in licensing this recycled brick concrete technology
- Ability to meet LEED sustainability requirements for their building re-cladding project
- Substantial savings by avoiding disposing large quantities of bricks into landfills