

PRACTICAL EXPERIENCES IN DESIGN, APPLICATION AND FIELD PERFORMANCE

EDWARD P. LITOW

Kleinfeldt Consultants Limited
Mississauga, Ontario, Canada

Successful long-term performance of a roof system begins in the design stages of a building. A proper understanding of the function and environment that the roof system is to enclose is essential when choosing an appropriate roof system. Design decisions will impact the application of the roof and consequently its field performance.

Case Study: Mayfield Recreation Complex, Town of Caledon, Ontario, Canada

Twenty-one years after construction of the building, an H.V.A.C. technician servicing a rooftop mechanical unit hopped off the unit onto the roof. The impact resulted in the breakage of the roof deck and subsequent repair of the roof.

Concerned as to the cause of the failure and by the presence of numerous hairline cracks in the roof deck in both the pool and the ice rink, the owner commissioned an engineering study of the roof that revealed:

- the structural deck had failed due to changes in its chemical composition;
- structural steel roof support hangers had severely corroded, rendering them structurally unsound.

These failures could be traced back to decisions made during the design stages of the original project.

From the perspective of a forensic analysis, the paper will discuss:

- what design decisions were made in the choice of roof system materials, including deck and flashings at the structural hangars;
- how the lightweight precast concrete planks performed in high humidity and freezing environments and how these environments affected the composition of the material;
- the cause and effect of ion transfer and condensation on unprotected structural steel and how they affected this roof system, specifically at the flashing details of the structural hangers.

KEYWORDS

Blister, chlorine, humidity, ion transfer, lightweight concrete, moisture control, vapor retarder, ventilation.

HISTORICAL BACKGROUND

Site

Mayfield Recreation Centre was conceived as an answer to the needs of the rural farming community of Mayfield and its surrounding area located in the Township of Chingacousy

approximately 45 kilometers northwest of the City of Toronto. The Centre was to be developed in conjunction with a rural high school, Mayfield Secondary School.

The site of these buildings located at the northeast side of the intersection of Mayfield and Bramalea Roads was central to the community and would accommodate its future growth as it eventually transformed from an agricultural community to a satellite community of the City of Brampton, itself a satellite city of Toronto. This was the long-term plan of the Toronto-centered region and was to occur through planned growth through regional governments. These were set up in the communities surrounding Toronto in the early 1970s. The community of Mayfield was to be incorporated into a new town called Caledon in a new regional government known as Peel Region.

DESIGN CRITERIA/CHOICE OF MATERIALS

General Requirements

The intent of the building was to provide a simple yet unique structure reflecting the existing rural nature of the community yet with the ability to fit into a future suburban community.

The needs of the facility required that the building envelope accommodate a high humidity environment (swimming pool) as well as a freezing environment (ice rink). The environment of the pool was to be maintained throughout the year at an air temperature of 30°C (86°F). (There was no indication as to what the mechanical designer had stipulated as a satisfactory interior relative humidity). This meant that the pool portion of the building would require mechanical heating of the air for 8 months (approximately mid-September to mid-May) of the year. Mechanical ventilation was provided in the space, however, dehumidification was not provided. The environment of the ice rink (arena) was to be used with an ice surface maintained at -8°C (17.6°F) from early September to the end of April every year. Heating in the arena was to be provided only over the public viewing stands via localized radiant heaters. Originally the site was to be developed in phases with the construction of the arena to take place first (1969-70), followed shortly thereafter by the swimming pool and the common area/foyer linking the two structures.

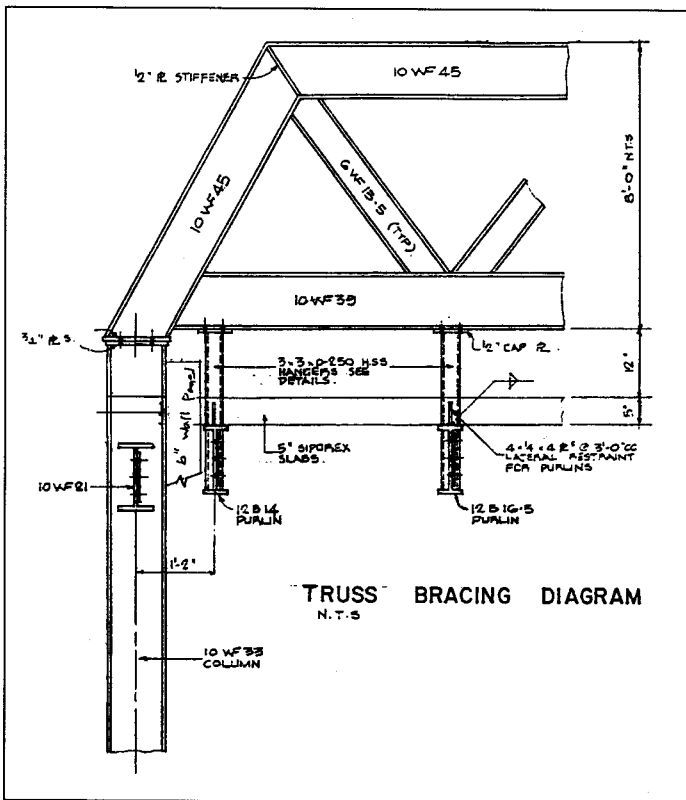
For the purposes of this report, the common area roofs of the complex will not be discussed as they were constructed with a different type of structural system and insulation configuration and did not exhibit the symptoms that were evident in the precast deck systems.

Structure

Roof Support

Uniqueness in the architectural expression of the design was achieved through the positioning of the structural elements of the roof structure. The designers opted to support the roof deck and roof system not from below as is the traditional approach, but rather from above by means of a truss system located above the roof. Exterior trusses allowed for good clear spans and ceiling heights within the building and eliminated the need for walls of extra height or a vaulted roof system to accommodate the trusses, had they been interior elements.

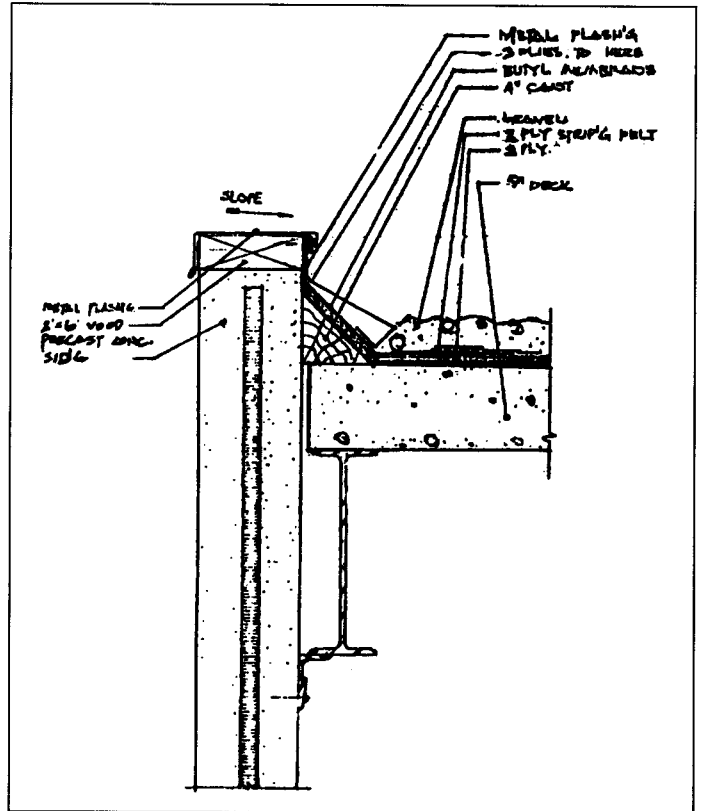
The deck and roof membrane were to be supported by a series of 12B16.5 steel I-beam purlins conforming to C.S.A. G40.12, which were bolted to hollow structural steel (HSS) square tube hangers, conforming to C.S.A. G40.12, which were in turn bolted directly to the exterior truss system.



Since regular steel could not be used on the exterior of the building without a protective coating to guard against the deleterious effects of nature, an atmospheric corrosion resisting structural steel was selected (i.e., "weathering steel"). Corrosion resistance was achieved by formulating the steel with a higher than normal content of copper. Upon exposure to the elements, the copper rich steel would form an oxidized layer of material that would act as the protective weathering finish. This coating of "rust" would then resist further corrosion of the material.

Walls

Simplicity in construction was achieved with the choice of a load bearing, insulated, precast concrete, tilt-up sandwich panel wall system.



Building envelope

Roof system

Deck—Precast lightweight insulating concrete panels 125 mm (5 inches) thick were chosen as the structural deck material since they could accommodate dead and live roof loads while providing improved thermal resistance over traditional concrete panels of similar dimensions. The era in which this building was constructed typically found insulation levels in roofs which used traditional insulating materials (e.g., fiberglass, fiberboard) to be relatively low. These panels were approximately 600 mm (24 inches) by approximately 3000 mm (118 inches). It appears that the thinking here was to provide a simple roof system that would provide commonly accepted thermal resistance levels as well as structural performance in one element. This eliminated the need for multiple layers of insulation that would require more materials, trades and time to construct.

The panels were constructed from a mixture of silica sand, cement and an aluminum foaming agent and were cast on edge to the specifications required by the design engineer. In this case, a density of 496.6 kg/m³ (31 lb/ft³) and a compressive strength of 3.1 MPa (450 psi [lb/in²]) was specified on the construction drawings. Actual design and shop drawings for the construction of the panels were not available to determine the amount and location of steel reinforcing supplied; however, in general, this type of panel was constructed with two reinforcing wires in the upper plane and three to six in the lower plane.

Waterproofing membrane—A conventional three-ply asphalt and aggregate (gravel) surfaced membrane was selected to serve as the waterproofing over the pool and ice rink. This system was selected for three primary reasons:

- It was the system of choice for the majority of roofers and designers in 1968. At the time of selection, there were few alternatives available with a proven record of performance.
- Detailing at the large number of projections on the roof (resulting from the need for the structural hangers) could be accommodated by the relatively simple methods of flashing with built-up roofing materials.
- Lightweight insulating concrete could accommodate direct mopping of the membrane to the deck.

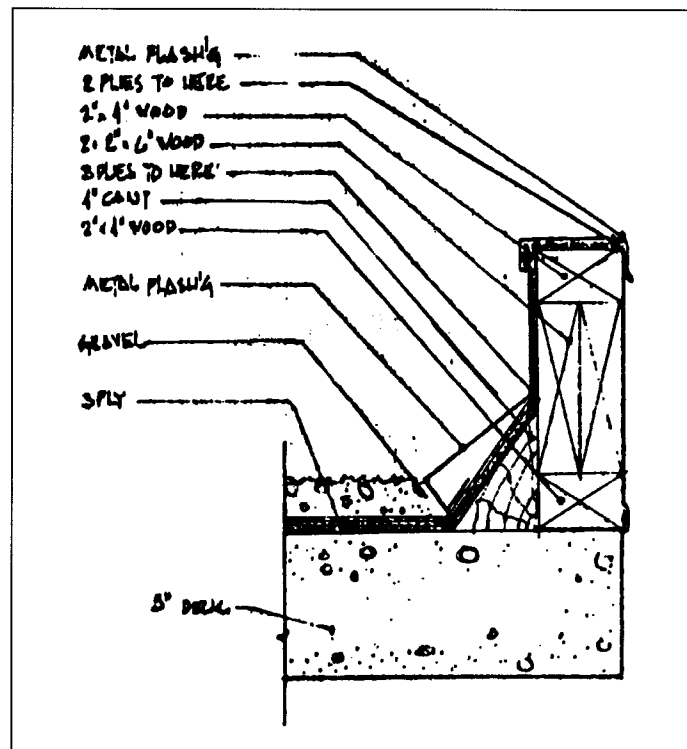
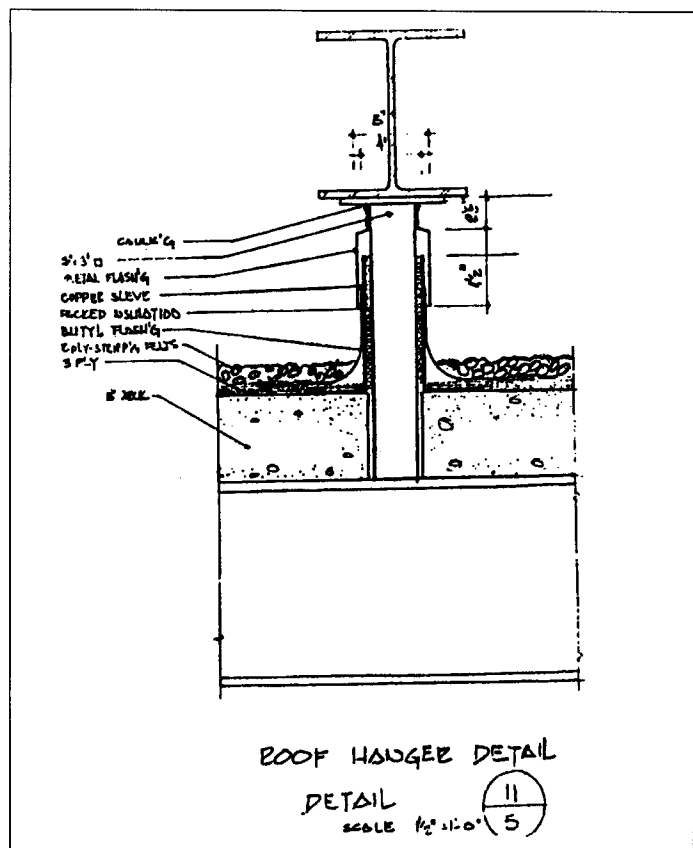
Flashings—The HSS square tube hangers were to be covered first with a layer of thermal insulation between the post and the field-manufactured copper sleeve. The sleeve was to be flashed with butyl flashings and capped with a metal cap flashing clamped and caulked to the steel post (see Detail 3). This design was commonly used in a built-up system at projections and was chosen for its reliability as a waterproofing element at horizontal to vertical transitions.

Flashings at the perimeters and rooftop equipment were to be constructed in the traditional manner with the membrane continued to the top of the wood cant, two plies of base flashing covered with the protective metal counterflashing (see Details 2 and 4).

Note that in none of these details is a vapor retarder or air barrier specified or indicated.

POST CONSTRUCTION PERFORMANCE

Upon completion of the complex and through observations made by the operations staff in the building, it was found that the humidity in the pool area would be quite high (in excess of 70 percent). The design conditions were not available in



the historical records and, therefore, could not be determined. The arena side experienced less severe humidity problems, which occurred throughout the season, particularly during the early and latter parts of the heating season.

These conditions were indicated during an engineering inspection of the structure as required by the Ontario Ministry of Labour (for life safety reasons, this is commonly performed on arenas/community centers as the buildings age) in 1982. Based on his visual observations, the engineer suggested that the existing conditions (i.e., migration of water vapor into wall and roof systems), be addressed before they affected the performance of the building.

TWENTY YEARS AFTER CONSTRUCTION

Due to the recurrence of minor and isolated incidents of moisture ingress from the roof into both the pool and ice rink portions of the complex and the spalling of the precast deck panels, a request was made by the town's Parks and Recreation Department to have the building examined by a structural engineer. This visual inspection was performed in March 1990.

In his inspection, the engineer noted that the Town had installed an air drying system that dehumidified and circulated heated dry air into the pool space (1989) and dehumidifiers in the arena (1988). According to officials of the Parks and Recreation Department who administer the maintenance of the building, these units had the desired effect of reducing humidity in both areas.

The engineer determined that the exterior structural elements were in good condition, but that the roof membrane was severely blistered throughout the areas of the arena and swimming pool. In addition to the blistered membrane, portions of the precast roof deck panels had spalled off, exposing their steel reinforcing wires. Discussions with building staff also revealed that a section of the roof deck had "fallen

out" in 1986 and had to be replaced. It was also observed that steel cross members (welded to the purlins) were installed in areas where the precast deck appeared weak (cracks and deflection) in both the arena and the pool areas.

Supports had also been installed at two drain locations in the arena. It appeared that a number of patch attempts had been made in an effort to restore the appearance of the deck after spalling. These areas were now loose as they had debonded from the substrate.

In addition to the concrete spalling and installation of supports in addition to the existing members, the engineer observed that transverse cracking had occurred in the arena particularly in the central spans over center ice level. Based on visual evidence only, the engineer expressed his opinion that the structural performance of the deck had become affected by the noted deficiencies and that the roof deck should be replaced within five years. Based on the visual inspection, it was recommended that the roof membrane be inspected to determine the extent of membrane damage that had to be addressed to keep the roof watertight for the five-year period until deck replacement would be undertaken.

Based on the engineer's recommendation, town officials requested proposals for a comprehensive engineering evaluation of the roof's condition both structurally and as a waterproofing system. The author's firm was awarded this project.

ROOFING AND DECK SYSTEM INVESTIGATION

After meeting with town officials, a scope of work for the investigation was developed. Initially, this work was to include the following:

- Evaluation of the structural deck via visual inspection and physical testing.

The testing would involve removal of 10 concrete cores from the deck, five from the arena and five from the pool. These cores were to be tested for compressive strength, density of the concrete as well as the amount of carbonation in the concrete. Past experience with lightweight concrete panels of this particular type had shown that the actual strength of the concrete was often significantly less than specified. If true in this case, it would be identified in the testing. The carbonation test would be useful in determining if there had been a breakdown in the concrete matrix.

The results of the tests would, therefore, be used to determine the structural integrity of the roof deck. If the deck were found to be structurally stable and adequate, a delamination survey would be undertaken to determine the extent of concrete delamination in the roof deck panels for future rectification.

- An infrared scan of the roof would be undertaken to determine whether there was evidence of water/moisture in the precast material and/or waterproofing membrane. Cores to verify construction of the membrane, brittleness and type of asphalt (if deemed necessary), and quality of bond to the deck were also to be taken.
- All information was to be included in a written report with recommendations for resolution of the problem.

WATERPROOFING SYSTEM INVESTIGATION

General observations

While the deck and waterproofing investigations were conducted in conjunction with each other, the waterproofing investigation was actually the first item to be completed. The first item slated for evaluation was the condition of the membrane. The rule of thumb average life span of a three-ply asphalt and aggregate surfaced membrane is 15 years, at which time replacement can normally be expected.

Visual observations of the two roof areas (pool, arena) found that the 21-year-old, three-ply membrane was in poor condition. Expected deficiencies, such as wind swept and exposed membrane at building corners (aggregate scour) and corroded areas of counterflashing, were minor in extent compared to the severe blistering of the membrane. While blisters plagued both roofs, the extent of the blistering was far greater over the swimming pool. Evidence of extensive water ponding was observed over the arena roof.

There was no visible sign of ruptures in the blisters. Ten cores were taken from random areas on the roofs in order to observe the quality of membrane bond to the deck, confirm number of plies and assess whether as-built bitumen quantities were acceptable. Visual observations revealed that the waterproofing had indeed been installed as per the construction drawings, which indicated direct to deck mopping of the membrane. The plies of the membrane were well bonded with sufficient amounts of bitumen showing between plies.

The infrared scan did not reveal any evidence of subsurface moisture in either the membrane or deck.

Based on this information, the decision was made not to proceed with further testing of the waterproofing layer. It was determined that due to the age of the roof and the potential for deck replacement, the most cost-effective solution for resolving the membrane conditions was replacement.

Causal factors for membrane blistering

Although there was not a major failure of the waterproofing in terms of preventing water entry into the system, there had been a failure somewhere in the system that allowed the blistering to occur. Where had the deficiency originated? Was the blistering of the membrane design or construction related or the result of a combination of factors?

Core samples through what appeared to be representative membrane blisters were taken in an attempt to answer these questions. The membrane in each sample was studied to determine whether the blisters were formed within the structure of the membrane (interply). In all cases, there was no evidence of interply blistering. In all cases, the membrane had failed in its adhesion to the deck at the membrane/deck interface. In all cases, it appeared that the deck had not been primed prior to the application of the roofing membrane. This was based on visual evidence only and was determined by scraping the top surface of the deck and examining the surface of the exposed concrete for evidence of primer staining.

If the bond between the membrane and deck had failed, why had it occurred? The first clue to be examined was the

original design. In the case of the pool, the interior environment was one of high humidity. The majority of the year found the interior with a heated, high humidity condition. In any heated interior environment, the natural tendency is for the warm humid air to migrate toward the colder drier exterior environment via vapor diffusion. This rate of migration or mode of transporting water vapor varies (vapor pressure) depending on how tightly sealed the building envelope is.

The tighter the seal, the less migration and, consequently, the greater the vapor pressure in the interior environment.

In most cases, moisture, in the form of water vapor, is carried in the air until it reaches its dew point, that point where the vapor in the air reaches its saturation point and begins to condense. Designers rule of thumb is that the dew point should be located outside of or in the outer third of the envelope. Most envelopes are designed to have the dew point occur in a layer of thermal insulation if it is located within the wall. The dew point for this roof system found it to be located in the top third of the insulating roof deck as per requirements. In cold climates, the rate of vapor transmission through the envelope is reduced through the installation of a vapor retarder.

Physical evidence and the construction drawings show that the roof system was not designed to allow for a vapor retarder. In actuality, the roofing system membrane was acting as the vapor retarder, which in this case would then be located on the cold side of the insulation and not the warm side as is the accepted design and engineering practice. Water vapor was free to enter into the roof deck and condense within the deck and on the underside of the membrane where it would freeze in the most severe winter months. In the autumn and early spring months, the deck and outer asphalt coating of the membrane would be damp in the vicinity of the dew point.

As the roofing system was heated via the heat of the sun, some of the moisture trapped under the roofing membrane would vaporize. As the vapor pressure increased, the asphalt's adhesive bond between the membrane assembly and the deck would be compromised.

Over time, the continual moisture drive, vaporization and condensation of the moisture under the roofing assembly would essentially delaminate the membrane from the deck, particularly if it was not well-adhered, forming membrane blisters.

This scenario could have been changed, if not eliminated, if in the original design of the building the designers would have included an effectively placed vapor retarder below the deck or placed a vapor retarder over the deck followed by insulation and then a membrane. A protected membrane roof could also have been designed, but not for use with this deck material. Providing the proper equipment to maintain the proper humidity levels would also have assisted; however, the problem with this approach is ensuring that the equipment is properly working and maintained. The latter element was introduced into the building in 1989, but by that time, the damage had been done.

Cause of Failure: Omission of the vapor retarder in the original design combined with uncontrolled high humidity levels in both the ice hockey arena and swimming pool ultimately resulted in the failure, in adhesion, of the membrane to the deck. Conditions over the pool were more

extensive due to the greater amounts of vapor drive into the roof system.

DECK INVESTIGATION

As previously discussed, the condition of the deck was a concern. To evaluate the physical condition of the lightweight panels, a total of 10 cores were extracted from the roofs. Cores 1 to 5 were removed from the pool roof deck and Cores 6 to 10 from the arena roof. These cores, where possible, were to be analyzed for their density, compressive strength and carbonation.

Despite the most careful cutting techniques, only four cores were deemed satisfactory for compressive strength and density tests (Cores #1, 2, 4, and 10). The remaining (Cores #3, and 5 to 9) were damaged during coring or removal and were deemed unfit to test.

Visual inspection of all cores revealed that of the five cores from the pool roof, one (Core #3) revealed corroded steel reinforcement and another (Core #5) revealed evidence of suspected freeze-thaw damage in the top 75 mm (3 inches) of its structure. Visual inspection of the arena roof cores revealed little information. These cores seemed to be in relatively good condition.

Tests for compressive strength, density and carbonation were conducted and are summarized in Table 1.

Core #	Compressive Strength	Density Excessive	Carbonation
	1.5 MPa	545 kg/m ³	Yes
2	1.3 MPa	545 kg/m ³	Yes
3	-	-	Yes
4	1.4MPa	547 kg/m ³	Yes
5 to 9	-	-	Yes
10	1.5MPa	558 kg/m ³	Yes

Table 1. Results of deck core analysis.

Compressive strength testing was performed according to the requirements of CSA A-23.2 - 14C. Density testing was performed from first principles where the mass of the sample is taken and divided over the measured volume of the sample (Density = Mass/Volume).

The designed compressive strength of the deck panels was to be 3.1 MPa (450 lb/in²) and the density 496.6 kg/m³ (31 lb/ft³). While in all cases the measured densities were consistent and found to be satisfactory, the compressive strengths were all consistent, but significantly under the strength found when the slabs were newly manufactured by between 51 percent and 58 percent.

All 10 samples tested for carbonation were found to exhibit excessive carbonation. Carbonation is the result of a reaction between free calcium hydroxide in wet cement and the atmospheric carbon dioxide. The depth or degree of carbonation is dependent on various factors, such as the design of the concrete mix, curing conditions, physical determinants regarding diffusion and square root of time. While even the best mixes will produce concrete that undergoes some carbonation, poorly mixed concrete will undergo a greater amount. The process is accompanied by shrinkage. Ultimately, excessive carbonation will affect the performance of the concrete structure by random cracking in the concrete from shrinkage, by breakdown of the cement/reinforcing

bond and by increased probability of causing steel corrosion.

Based on the results of the testing (i.e., low compressive strength, higher than normal amounts of carbonation, and when factoring in the yield strength of the reinforcement assumed to be 0.75 times the "balanced" condition as per CSA CAN3-A23.3 clause 8.4.2), it was determined that the deck panels would be loaded to the limits allowed by the building codes for the full design live loading of snow with little capacity remaining. This "little remaining" capacity would be further reduced if the panels had experienced any freeze-thaw damage (e.g., Core #5 pool roof).

If, in the overall scenario of the roof, a number of the panels were in this "on the edge" loading position and the loading on the roof then exceeded the actual load carrying capacity of the panels or the reinforcing wires corroded further, or the concrete spalled further, the structural integrity of the roof could be compromised. The engineers recommended that further testing to determine the load carrying capability of the slabs be performed.

The next phase of testing involved construction of an approximate 3 m x 3 m x 200 mm (10 ft x 10 ft x 8 inches) water reservoir on the roof and filling it with water to a depth of 175.2 mm (6.9 in.) (to simulate the maximum design live snow load of 185 kg/m² [38 psf]). Roof system deflections were monitored directly under the test site by an ultrasonic sender/receiver hardwired to a remote read out device that recorded deflections. Test results were plotted on a linear scale of depth of water to slab deflection.

The testing revealed that the slabs were still in the elastic range over the duration of the test. This was confirmed when it was observed that the deflected plank returned to its original position after the load was removed. It was, therefore, concluded that the roof system would support the required combinations of live and dead loads as stipulated in the Ontario Building Code.

Based on those results and the information from the previous series of concrete tests, it was concluded that while the concrete exhibited acceptable performance under compressive loading, the fact that the structural compressive strength of the concrete was lower than required (the original deck manufacturer could not confirm the designed compressive strength of the slabs), the known incidence of deteriorated concrete through freeze-thaw cycling and the known effect of carbonation, the reinforcement condition within the panels would continue to be unbalanced.

It would be possible in this case that the panels could fail without prior warning in a "brittle" failure manifested in the form of cracking or excessive deflections. In the worst case scenario, the panels could collapse without warning and fall to the surfaces below. Since this was a life safety issue, the engineer's recommendation was to replace the deck.

Causal factors for deck failure

Why had the deck failed? Had the environment in which it performed contributed to its demise? Ultimately, the deck failed because the initial concrete mix had contributed to higher amounts of carbonation than expected, which changed the compressive strength of the material, which resulted in the cracking, spalling, etc.

The environment in which the panels performed accelerated/augmented the failure. Lightweight concrete by nature is more porous than regular concrete. As discussed in the roofing analysis, water vapor can enter into this material

readily. If the vapor condenses into water and freezes, the expansion of the ice will result in spalling/delamination of the deck materials. This was confirmed in at least one of the cores taken from the deck.

Another factor on the pool side roof deck, in addition to the amounts of moisture migrating into the deck, was the composition of the moisture. The vapor was also highly reactive as it carried chlorine ions into the deck. Chlorine is a highly reactive ion when it combines with ferrous substances. Since the deck panels were reinforced with steel, any areas where its protective coating (i.e., the concrete) was damaged would begin to react with the water and chlorine. As the corrosion progressed and the steel expanded, the weakened concrete would delaminate. This was evidenced by the number of areas where the deck had spalled.

Ultimate cause of failure: Moisture related. The designer's decision to install panels in humid environments without the benefit of detailing an air barrier and vapor retarder system ultimately led to their demise as a structural element.

STRUCTURAL HANGERS

The decision by the town was to replace the roof immediately. Contracts were awarded for the design and construction of the new roof.

In the course of demolition of the old roof, a hidden defect in the structural system was revealed. The HSS hangers had lost a significant portion of their section behind the copper flashings. This was most evident on the pool roof. The degree of deterioration was highly obvious on this roof. The arena hangers had also experienced section loss, but to a lesser degree. Structural analysis of the damaged hangers determined that the percentage loss of steel was too great on more than 60 percent of the hangers and that these affected hangers would have to be replaced.

Our investigation of the factors and events that resulted in this structural element's failure found several contributing factors. The original detail at the hangers (see Detail 3) showed that the copper sleeve was to be insulated. While this was the case on the pool roof, it was not true of the arena roof. The sleeves on the arena roof were not insulated and in actuality were fit tight to the HSS hanger, a construction deficiency.

The corrosion of the steel was due to two factors: the first was related to a design deficiency that did not provide for air seals at the points where the hangers protruded through the roof decking; and the second was due to ion transfer through contact of dissimilar metals. These factors are explained in the following paragraph.

Humidity and ion exchange

As discussed earlier, humidity/moisture was allowed easy access to the roof system. The case was no different at the hangers. The original design, while calling for insulation at the sleeves, did not call for sealing of the opening through the deck to prevent water vapor from entering into the space between the sleeve and hanger. Unlike vapor diffusion, which was discussed earlier, air flow, particularly if moisture rich, can rapidly transport large quantities of moisture. Moisture would condense in this space, accumulate, soak the insulation, freeze, etc. Any exposed metal on the hanger would be subjected to oxidation, and hence, corrosion. The pool environment with its chlorine-laden air would accelerate the