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ENGINEERING & ENVIRONMENTAL SCIENCES

WIND UPLIFT EFFECTS

ON BUILDINGS

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Pario Engineering and Environmental Sciences was recently involved in a case of wind uplift damage. This paper will discuss the identification of the cause and the reconstruction of the building to the requirements of the 2005 National Building Code of Canada (NBCC). The case is noteworthy because the damage occurred to a brand new aircraft hangar that was designed and constructed in 2008; the building was exposed to about only half of the design wind loading; and, the building had to be repaired and commissioned back to service as soon as possible. The building structural components were designed using structural analysis calculations, as required by the 2005 NBCC. However, the building also contained parts that were only prototype tested by the Underwriters Laboratories (UL); i.e. these parts and their components did not pass a diligent structural engineering analysis. Such building parts or assemblies are allowed to be designed by testing only if the parts (quote from Article 4.1.1.5, “Design Basis” of 2005 NBCC, Division B): “... are not amenable to analysis using a generally established theory...” (e.g. Strength/Resistance of Materials; Statics and Dynamics; Theory of Elasticity; and other structural sciences). We note that this Article of the 2005 NBCC differed from the corresponding articles of previous codes by giving a preference to the results obtained from theoretical structural analysis versus the results obtained through prototype testing. In previous codes such a preference was not explicitly stipulated.

In this particular case, after reviewing and determining that there was a general Code compliance of all structural components designed with the use of structural calculations, we decided to apply structural analysis calculations on a component of a two-component part that was allowed in the hangar roof construction based only on the results of the Underwriters Laboratories (UL) testing. Our decision was also justified due to insufficient information in regards to the materials used for this particular project in the production of the subject components. We proved that the failed component of the subject part could have been analyzed (i.e. was amenable to analysis) using generally established theory and that the component was the “weak link” that caused the damage.

It is important that a forensic structural engineer explores all possibilities to apply structural analysis calculations in order to assess the structural capabilities of building components. In the event of missing or incomplete information regarding components that are part of a group or assembly tested only through a prototype, he/she must be prepared to challenge established construction tables based on prototype testing. The engineer must explore all possibilities to identify a scientific method to apply academic knowledge to the structural engineering evaluation of a component within a building assembly or part.

Introduction

The following case study describes Pario's involvement in the structural engineering investigation of roof structural failure of a federal building (a brand new military aircraft hangar) that occurred during an exposure to a wind storm on December 28, 2008.

Pario completed an investigation that met the stringent deadline (three weeks from first site attendance) imposed by National Defence Canada (NDC). Our investigation of the incident occurred in concert with other investigations carried out by other forensic firms. Pario was the only forensic firm that was able to pinpoint the building components that failed first and caused the failure of other components; to prove our hypothesis with structural engineering calculations our finding, which were further confirmed by a physical testing; to explain the mechanism and the sequence of the failure; to assess the damage to the structure; to evaluate the effect of the failure on the overall structure of the building; and, eventually, to approve the new design required to reconstruct the hangar roof to a condition that meets the requirements of the 2005 NBCC (Note: Federal buildings must meet the minimum requirements of the National Code).

In addition, an independent testing laboratory was retained to complete the above mentioned physical testing of the maximum pull-out force the failed building component was capable of resisting. The testing results fully confirmed the results achieved from our theoretical structural analysis calculations; and, we could rebut theories prepared by the structural designer of the hangar. We were also able to answer questions and inquiries of National Defence Canada and Defence Construction Canada (DCC).

Pario produced a total of 5 comprehensive reports that contained over 120 pages and sketches and reviewed hundreds of document pages. Our first report identified the cause; as well as explained the mechanism of failure; and, pinpointed the exact group of identical building components that failed. The first report was presented to a large forum of representatives from NDC and DCC, some of who had come from as far as Western Canadian military bases.

The Hangar

It cost the military $6.2 million in construction costs to complete this steel aircraft hangar. It was located on the grounds of the 8 Wing of CFB Trenton. The construction was completed two months before the loss occurrence. The hangar was earmarked to be a long term home for any one of Canada's four, strategic and tactical CC-177 Globemaster IIIs (Boeing's C-17, officially designated as the CC-177 in Canada). The Globemaster IIIs were purchased to replace the CC-150 Polaris and CC-130 Hercules, which the Royal

Canadian Air Forces have used in the past for strategic airlift around the globe. The hangar was designated to be the long term home for this aircraft during initial CC-177 III operations (e.g. Afghanistan mission).

Figure 1. CC-177 Globemaster III.

The size of the aircraft was impressive: Width - 170 feet (51.75 meters); Length - 174 feet (53 meters); Height - 55 feet (16.79 meters).

Figure 2. Inside the aircraft

The gross floor area of the hangar was 4,200 square meters (45,350 s.f.). The width of the one-span building was 66 meters (217 feet), the length was 63.5 meters (209 feet) and the height was 28 meters (92 feet) at the ridge. The hangar below grade reinforced concrete and the above-grade steel structures were designed, fabricated and erected by Canadian companies. The building gable roof contained north and south facing slopes. The exterior wall and roof cladding (decking) comprised of two types of corrugated steel panels. The roof cladding and its attachment to the roof structural framing was a proprietary "standing seam" roofing system that was supplied by MBCI (Metal Roof and Wall Systems) of the USA and was called "Ultra-Dek". (The "Ultra-Dek" system was a registered mark of Metal Building Components L.P. and represented by NCI Building Systems, USA). The cladding was installed by the Canadian General Contractor.

The huge retractable front door was designed, supplied and installed complete by an American company (MEGADOOR Opening Solution Incorporated, Georgia). The door comprised of three sections and had an overall size 52m x 21m (W x H). The west elevation of the hangar consisted almost entirely of the huge door.

An important fact regarding this type of "standing seam" roof cladding is that it cannot provide the roof structural resistance attribute that is known as "roof diaphragm". This feature would be routinely provided with roof decks that are typically welded or fastened with bolts to the roof purlins (beams). Therefore, roof steel bracing was crucial to the hanger roof structural performance and to the flawless performance of the roof cladding attachment to the roof purlins.

The installed SSR (Standing Seam Roof) roofing system comprised of long and narrow deck panels installed side by side and transversely over the roof purlins. The deck panels were interconnected along the seam. The seam was connected to each roof purlin located under the deck with a two-component steel roof clip. It appeared that the hangar structural designer had evaluated the ultimate loading conditions for the roof and had selected the components of the roofing system from published Ultra-Dek tables. The tables' values for wind-uplift resistance were compiled on results obtained by laboratory loading test conducted by Underwriters Laboratories (UL) on a full-scale roofing prototype of a limited area (10′ x 10′).

Figure 3. The hangar within hours after the incident.

What happened?

It was reported that during a wind storm, while the hangar doors were closed, two large areas of ruptures opened; one within the hangar roof cladding; and, the other within the huge front door. Luckily the CC-117 or any other aircraft was not stationed inside the hangar at the time of this incident. That was luck, since airborne "shrapnel" from the fractured door blew 50 meters inside the hangar. The largest piece of shrapnel weighed 30 pounds.

At the time of the failure occurrence, the building was undoubtedly experiencing strong gusty winds coming from the west direction. The aftermath of the failure that showed both ruptured areas was recorded by the Base video surveillance. The actual moment of initial occurrence of the first rupture (probably in a fraction of a second) was not recorded since the surveillance cameras required motion to activate; therefore, the rupture that occurred first and which probably caused the second rupture (almost instantaneously) was not caught on the surveillance video. There were no eyewitness accounts at the onset of the failure, as well.

The client, NDC, asked Pario to establish the following:

- Which rupture occurred first, within the door or within the roof, since two separate contractors were involved in their construction?
- Did the first failure cause or contribute to the failure within the second rupture area?
- Was the hourly wind pressure and associated wind velocity at the time of the loss occurrence above the 2005 NBCC maximum values that such building was anticipated to resist at that location in Ontario; and, if not, what caused the brand new roof and door to sustain damage? Was it due to an unrecorded enormous burst of wind, designer error, erection error, poor workmanship, material fatigue or something else?
- To assess the damage to the structure; and,
- To evaluate the effect of the failure on other structural components of the building.

Working 24/7

In the early afternoon hours of December 29, 2008, I was at another loss in Smiths Falls when my cellular phone rang and I was advised: “We got a call from CFB Trenton and they require a structural engineer to attend as soon as possible.” During this emergency inspection I established that there was no danger of collapse or further failure of any of the hangar main structural framing components.

A second site visit was conducted on January 1, 2009, during which an articulating boom bucket truck with a reaching height of over 100 feet was used to inspect the damage. For almost six hours, from the bucket of the truck, I inspected the overall hangar structure, the damaged area of the roof, the top of the exterior walls adjacent to the damaged roof area and the damaged door.

Figure 4. Area of roof rupture. Emergency crew in action.

The ruptured roof area was about half of the overall damaged roof deck area, which itself was roughly 1,100 square meters (11,860 s.f.). The exterior wall cladding adjacent to the damaged roof was also damaged (400 sq. m.). Within one location there were several buckled or bent eave struts and a wall girt. These were damaged due to the whiplash force that the airborne roof decking produced on that location of intersecting roof and exterior wall. The primary structural members of the hangar (e.g. columns, main roof girders) were not adversely affected by the loss. A large part of the door middle section (567 sq.m.) and its attachment to the vertical door mullions (supported by the building columns) was damaged and displaced.

From collected climatic data recorded at the Base, we established that the hourly wind pressure generated by the storm at the time of the failure occurrence was less than half the pressure (and the associated mean wind velocity) that such a building in Trenton was expected to resist if constructed in conformity with the 2005 NBCC. In other words, the storm was not extraordinary powerful or rare in occurrence – a storm of such magnitude may occur annually. The recorded mean wind speed at the time of the failure was 33 knots (61.1 km/h), which equals an hourly wind pressure of 0.19 kPa. The required building Code resistance to specified wind forces for the hangar and its components was 0.47 kPa of hourly wind pressure, which equals 96.3 km/h mean wind velocity. The highest recorded gust velocity during this storm was approximately 96 km/h; however, exposure to wind gust is included in the Code formulas by magnifying the aforementioned wind pressure value with various factors (up to 2.5).

We temporarily restrained our analysis from any contemplation of unrecorded extraordinary wind events (e.g. microbursts; squalls; down-bursts, short ground base vortex) or poor workmanship, until checking for adequateness of the entire design and construction of the hanger and the door. If the aforementioned adequateness was univocally confirmed, then we would have focused our analysis on extraordinary gusts of wind or poor workmanship.

We worked 24/7 in order to meet the deadline. Pinpointing the “Weakest Link”.

From the beginning, the opinion of those involved in the hangar design and construction was that the MEGADOOR door system probably contained some sort of deficiency, which caused the door to rupture first; and, that the door failure subsequently caused the roof cladding to blow off. In order to respect this “situation”, we commenced our engineering evaluation by reviewing and checking the product and the door instalment of the American door manufacturer. Our review of the door structural design calculations confirmed that the door would have been structurally sound at the over twice lower wind velocity (subsequently wind pressure) recorded at the time of the failure. We compared the installed door parts with the designed door parts and we found that there was a general conformity with the exception of noncompliance with a clause of the CSA S157-

05 (Strength Design in Aluminum) standard that was identified within one repeating bolted connection detail. That noncompliance could not have affected the performance of the brand new door when the door was exposed to a twice lower wind pressure than the maximum anticipated to occur in Trenton.

Figure 5. Damaged roof area cleared from debris.

We then switched our focus on the hangar structure. We compared the constructed (as- built) building components and connections with the components and connections as stipulated in the design drawings and we found that there was general conformity and no substantial difference between design and erection. This was also confirmed when we went through the submitted construction logs, documents and material specifications, including grades of steel used in the hangar structural framing.

Next step was to review the design of the hangar. We analyzed a number of features of the hangar structural design and construction, which if found inadequate, we believed, would have had the potential to compromise an area of the roof decking and its attachments to the roof beams. We ruled out inadequateness of the vertical bracing between the hangar columns; inadequateness of the horizontal bracing that secured the roof rigidity; the occurrence of inadequate (excessive) or deferential horizontal movement along the top of the west exterior wall (connected to the damaged roof area); and, the occurrence of excessive rotational movement of the SSR deck relative to the building columns.

We concentrated our efforts on the evaluation of the components of the SSR roofing system and their individual ability to resist transferred wind uplift loads.

Due to the numerous building components involved in the hangar framing and overall building envelope, our years of construction supervision and structural design experience with a variety of construction materials and methods were invaluable in assessing Code compliance of hangar framing and door structural members. The ability to promptly and confidently eliminate adequate (Code compliant) building components, allowed us to focus on building components that we suspected to have caused the reported failure.

We note that during the preparation of our first report, complete structural designer calculations of the hangar structure, including wind-uplift loads and calculations relative to the hangar roof cladding were not submitted to Pario. We conducted our own calculations. We evaluated the acting wind-uplift loading at the time of the failure. In calculating the wind uplift pressures, we used software published by the National Research Council of Canada (the same publisher of the 2005 NBCC) specifically developed for the calculations of roof specified design wind uplift pressures. The use of this software precluded any arguments and disagreements between the parties involved in this case (regarding calculations that use the graphs of Figure I-11 of the Structural Commentaries of 2005 NBCC) since any party would have reasonably considered these results undisputable.

A two-component roof clip, which was used throughout the entire roof, held down the roof decking attached to the roof purlins. We grew suspicious of one of the clip components that looked “weak”. As mentioned above, a prototype of this type of the Ultra-Dek roofing assembly, which included the subject roof clip, was tested by the UL; and, therefore, the clip was allegedly adequate for the wind-uplift forces at the time the failure occurred. However, full information in regards to the materials used in the production of the roof clip components installed on this hangar was not obtained; in other words, there was not enough evidence that the installed roof clips exactly matched the ones that were tested.

Since we were faced with insufficient information to determine whether the roof complied with the UL construction requirements, we decided to try to evaluate each component of the prototype tested assembly with the use of theoretical structural engineering sciences. We establish the mechanism of loading transfer between the roof assembly components and eventually calculated the maximum force the “weak-looking” roof clip component was exposed at the time of the failure. These calculations were based on generally established structural engineering theory, as stipulated and required by Article 4.1.1.4 “Design Basis” of Part 4 of the 2005 NBCC. The results of our calculations were the preferred ones; they ruled over the UL prototype loading test, at least in regards to the “weak-looking” component.

Our calculations established that the “weak-looking” component of the roof clips constructed within the roof corners failed to resist the maximum upward (pull-out) force of 1.9 kN (428 lbs), which was transferred to the subject component during the storm when the mean wind velocity reached 61 km/h. The steel of the weak component yielded when the applied pull-out force reached 1.9 kN. The steel yielding caused the hook of that component to open and to release the portion of the roof deck, which the hook was holding.

Figure 6. Damaged standing seam

Moreover, throughout the entire roof, wherever installed, that component of the roof clip was incapable of resisting the maximum design wind-uplift loading anticipated to occur in Trenton with probability of occurrence once in 50 years, as required by the 2005 NBCC (2006 OBC respectively). Not only the corner zones but the entire hangar roof cladding had to be replaced and/or reinforced.

We pinpointed the “weakest link”.

Figure 7. The “weak” top component of the two-component roof clip.

There was disbelief from some of the military personnel gathered for the January 20, 2009 meeting, when the news about that weak component was delivered to them. An instruction to send several “weak” components of the roof clip to an independent testing laboratory followed soon after. If we were right, the lab results would confirm that that component of the roof clip opens its hook when a force of approximately 1.9 kN is applied.

The lab conducted physical testing of the maximum pull-out force that sole component was capable of resisting before opening its hook to beyond 90 degrees. The results fully confirmed our theoretical structural analysis.

Sequence of Failure Development

In the morning of December 28, 2008 the building and its components were experiencing the turbulent effects of the wind. The roof clips within the southwest and northwest corners of the roof were slowly opening up their steel hooks under the force of the upward pressure caused by the wind when its mean velocity commenced to reach 61 km/h. The moment came when one of the roof corners clips was the first clip to open its hook beyond 90 degrees; the hook released its grip on the portion of the deck it was holding. A "domino effect" to the hooks of the adjacent clips (to the first failed hook) followed since the area of decking that the adjacent clips had to hold suddenly increased. As a result, an undetermined area of the roof deck abruptly went airborne.

As anticipated by the results of our structural analysis, the roof clips located to the interior of the hangar roof were experiencing significantly lesser (40% less) wind-uplift forces than the clips within the corner zones. The steel material of the hooks of these roof clips did not yield; therefore, the hooks did not open; thus, sustaining their grip to their portion of the roof deck. That is where the destruction of the roof cladding stopped.

The moment the first rupture in the roof cladding occurred, the wind effects on other portions of the building, including the huge door, were suddenly significantly magnified by the dynamics of the occurred immediate suction (pneumatic hammer effect) created by the roof cladding rupture. As a result, the hangar door rupture followed.

Conclusions

The above case study exemplifies two important requirements for a successful forensic structural engineering team: (1.) The capability to pinpoint the first failed building component (group of components) by conducting a thorough, meticulous and scientific forensic investigation; and, (2.) The need to have solid experience and knowledge of design and construction practices with all types of construction materials.

The need to point to which component failed first is important since different contractors may be involved with the construction of a structure and sometimes the work of one contractor depends on the work quality of another contractor.

Years of structural design and construction supervision experience are crucial to quickly assess whether the existing components are compliant or not to certain requirements of a Building Code. The ability to promptly eliminate adequate (Code compliant) building components allows the engineer to concentrate on building components that are suspected to have caused a reported structural failure. Years of experience will help an engineer to have the confidence to challenge established practices (e.g. construction tables based only on prototypes testing).

This case also provides an excellent example of the importance of analyzing a structure using generally established theory and to use prototype by a loading test only if a system is (quote) “not amenable to analysis using generally established theory”.

Closing Remarks

The identification of that particular failed component was of immense importance. In the event that: the “weakest link” was not identified; the failure would have been attributed to an unrecorded burst of wind or to poor workmanship during erection or other vague possibility; and, if the hangar was reconstructed to its pre-loss condition with the inclusion of the defective roof clip component, next time a wind storm of similar magnitude occurred, further expenses (taxpayers money) to repair wind damages would have been incurred.

National Defence Canada requested that Pario get involved with the reconstruction of the hangar roof. We checked and approved the new design for the roof cladding and since the completion in 2009 of the hangar reconstruction; the CC-177 Globemaster IIIs enjoy a safer shelter.