Parks College Engineers Support Design of Our-Lady-of-the-Snows National Shrine at Belleville, Illinois

by

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ABSTRACT

A new building was completed at Our-lady-of-the-Snows National Shrine (OLSNS) at Belleville, Illinois in Spring 1998. This new building contains a cavernous room for 6000 votive candles, and is accentuated by an 85-foot high tower protruding through a Venturi-like opening in the roof. The tower is of a modified helical design concept, intended to resemble a candle flame by the inventor, The late, Mr. William Severson, Artist and Sculptor. The building was designed by Mr. Art Stauder, Architect.

This paper will describe studies conducted at Parks college under the supervision of the Authors. These studies relate to both the Strauder Architectural Building and the “flame-like tower”, appropriately called “FLAMMA” by Artist/Sculptor Severson. The initial study was that of the temperature environments in the building, and was entirely analytical. The late Dr. Arthur Monsey, Consultant to Severson, suggested additional studies be run on “FLAMMA” to ensure public safety, notable effects from wind-induced vibration, should be verified. Consequently, analytical studies were made to assess the vibration, static and dynamic loads, and flutter and divergence properties. Subsequently, wind tunnel and water tunnel tests were made at Parks College, using scaled models of “FLAMMA” to verify the analytical work. Ultimately, experimental studies were expanded to assess wind effects within the building and those induced by FLAMMA. Initially, in the water tunnel tests, complex flow patterns around FLAMMA were observed using Flow Visualization Methods, indicating a upwards corkscrewing type flow believed to be introduced from FLAMMA’s shape. Additional wind tunnel tests included a completely scaled model of the open-front candle chamber with a FLAMMA tower model in place. Wind speeds within the building were measured, and flow visualization, using smoke, was further employed to qualitatively track the flow patterns. Finally, the feasibility of using small “windshields” on the candles was investigated.

The Shrine has been functional for one-half years and has withstood the test of some episodes of high winds. Many of the predicted results of these studies have now been verified. It is believed that this study has significantly contributed to the safety of the building and has pointed to a number of operational concerns. The Authors have photographs and VCR tapes of the models and testing to include in the presentation of results. A number of Park's College students participated in the work, and are cited for their contributions. Parks College is pleased to have performed a community service to a worthwhile cause. This paper is an extension of an earlier paper presented at the ASEE Conference, Ref. (1), and is being given at the urging of the conference Chair of that meeting, since there was believed to be a unique community service rendered which should be reported more widely.

THE TEMPERATURE PROBLEM

The OLSNS existing shrine buildings are natural convection ventilated by having open ends. The temperature within these shrines often reaches 35 to 40 degrees F. above the outside ambient temperature. In addition to the uncomfortable conditions imposed on shrine visitors, there is considerable breakage of the candle jars, presumably due to the high temperatures. Dr. Andres' extensive experience with fluid-dynamics and thermo-dynamics was put to good work with this problem

The new shrine was designed similar to a hearth, with an open front and a venturi-like opening in the ceiling. The interior ceiling slopes slightly upward toward the opening. The opening thus provides a chimney like exhaust for the room, Fig (1). A second purpose of the venturi opening is to provide for the protuberance of the flame like 'sculpture' termed 'FLAMMA'. The base of Flamma is anchored to a concrete pedestal, which is near the center of the shrine room.

The initial task was to predict the interior temperature for the new shrine. The power output of a candle was determined by recording burning time and calculating the heat content of the paraffin. Each candle was found to produce about 60 watts and the initial design called for 10,000 candles. The number was later reduced to 6,000.

The interior temperature was estimated by considering the shrine room to be a large fireplace. The venturi was considered to be the chimney. A draft equation (American Society of Heating and Ventilation Engineers) was combined with the energy equation to determine the temperature rise of the air and the attendant volume flow. To implement the equation, the head loss for the flow path also had to be estimated. No wind was considered and the exit air was assumed to be uniformly heated. For 10,000 candles, the result was a 27 deg. F temperature rise and a 9 ft/sec velocity in the venturi opening. The design was later changed to accommodate 6000 candles with a predicted temperature rise of 20 deg. F.

Flamma\wind Interaction

Wind effects on FLAMMA were an early concern, especially the possibility of regular vortex shedding. It was decided to test a small model of Flamma in the Parks water tunnel. Dye was used to make the flow visible.

Fortunately, periodic shedding of vortices was not existent over any great extent of the sculpture. This was apparently a result of the continuing changing geometry (twist) as Flamma reached skyward. There were however vertical flows, both upward and downward, on the lee side. This suggested that Flamma could influence the flow within the shrine itself. With a wind direction that produced downflow at the base, the flow would enter the shrine room around the pedestal. Tiers of candles that initially were to surround the pedestal were removed from the design. Based on these findings it was proposed that a scale model of the shrine building, including Flamma protruding from the venturi, be tested in the subsonic wind tunnel. It was also proposed that burning candles be tested in the wind tunnel to explore shielding of the flames.

Wind Effects in the Shrine

The tests consisted of determining the effect of wind speed on the candles and the effect of wind currents on the space within the building. Quanative data of wind speed within the building and the speed for candle extinguishment and some qualitative data (visualization of air currents using smoke) was obtained, Fig (2):

(a). Building flow tests

The largest scale building that would fit the 40 inch wide Parks wind tunnel was constructed. Wind speed at selected positions within the building was measured using a hot wire probe. The highest speeds were found near the ceiling where the opening for Flamma is located. The highest speeds were recorded on the sides of the support pedestal with lower values front and back. The open front of the building will face East and the wind effects are turned to that direction. Tests showed that when the wind had a component from the East (toward the building front), there would be outflow through the roof while if the wind was Westerly, there would be inflow. The highest speeds occurred with the inflow due to a direct westerly wind, which produced windspeeds as high as 73% of the westerly flow in the vicinity of the pedestal near the ceiling. With the frontal Easterly flow, wind speeds as high as 45% of the outside flow were found near the ceiling some distance to the side of the pedestal. Typically, the interior wind currents diminished toward zero near the floor. In every case, the speeds increased rather abruptly near the ceiling.

A landscape extension was constructed and the model was tested with a simulated SSE, S, and SSW flow. The flow for these orientations was observed with smoke. Again some outflow occurred with the SSE flow while inflow occurred with the SSW flow, again demonstrating that Easterly components produce inflow into the building and outflow through the roof opening while westerly components produce the reverse. Three effects are assumed to produce the inflow when the wind has a westerly component:

a. The blocking effect of the flame.
b. The blocking effect of the roof wall along the front of the building, which was modeled as solid.
c. The low pressure in the front of the building caused by the separation of the flow as it leaves the roof of the building. This cases a low pressure inside the building.

(b) Candle tests

A burning candle was placed in the tunnel and the wind speed was increased until it extinguished. This occurred at just over 13 mph for both a new and a half burned candle. The mechanism appears to be horizontal vortex inside the jar that moves the flame forward and off the wick. (In the direction of the oncoming wind). Adding turbulence to the wind greatly reduced the extinguishing speed. With significant turbulence, the candle blew out at 3 mph.

A small metal shield was affixed to the candle jar mouth. This shield was about 1 3/8 inches high and tapered off to zero at 90 degrees from the high point. The shield extended half way around the jar. With this shield, the flame did not extinguish until a tunnel speed of 39 mph was reached when the high point of the shield was oriented at about 30 degrees from the wind direction. When the high point faced directly at the wind, the extinguishing speed was 24 mph and when the jar was rotated 180 degrees such that the shield was on the downwind side, the extinguishing speed was only 3 mph. Again, without the shield the flame extinguished at just over 13 mph.

These tests indicated a shield could be helpful if found necessary. The shield tested is sensitive to flow direction and might have to be tailored to suit various positions within the building.

The limited testing suggested wind problems were likely to exist and some possible design considerations were recommended:

A. A plexiglass or glass shield along the front of the building, extending to a height slightly above the candle tiers. If such a shield were to be used, it should not extend all the way to the ground.

B. With wind components from the back side of the building, a strong downflow is likely to exist inside the building. Possibly an interior baffle to direct this flow along the ceiling might be helpful. A open roof wall might improve the situation. With wind components from the back of the building, the sculpture flame is likely to add to the downflow tendency, with the strongest contribution occurring when the lower part of the flame is perpendicular to the wind component

C. At some future point the candle tiers could incorporate custom designed baffles to increase the blowout resistance to the winds. To do this adequately, a more detailed knowledge of the flow inside the building with various winds will be needed. The effect of turbulence as induced by surrounding terrain, could also be very significant.

LOADS AND DYNAMICS

Effort was made to determine the loads on the structure, employing both theory and experiment, in order to compare our predicted values with those used by Dr. Monsey and the Architects. Likewise, based on conversation between the various parties as far back as 1996, effort was also made to investigate the wind-induced vibration and stability of the structure using both theory and experiment. A brief summary of these efforts is discussed here. VCR Tapes will be used in the presentation to further aid the discussion. Preliminary water tunnel tests with scaled models set the pace for analytical and experimental vibration studies, and analytical and wind tunnel studies of scaled models. Predictions for the full size structure were made by scaling the models to full size as well as by direct calculations for the full size case. This gave a balanced check of the results. This effort was largely done by Dr. Ferman, the temperature work by Dr. Andres.

(b) Candle Tests

Preliminary Water tunnel Tests.

These tests were conducted by Dr. Andres using a plastic Model and a paper model, both some 12-in. in height, and scaled approximately in diameter and with the helix shape. The results showed that an upward corkscrewing motion of the fluid resulted as noted earlier in the temperature section discussion. The paper model bent statically to a large deflection at low water speeds, indicating it was too soft to be of use as a dynamics model. The plastic model, being much stiffer, did provide better insight. It deflected statically 1 in., and showed a Karman Vortex excitation with amplitude of roughly 1/4-in. when the flow was parallel to the upper tip section. This occurred at about the highest water speed of 1.5 ft/sec. Likewise, the model showed about 3/4 in. static deflection, with a Karman Vortex vibration motion of about 1/8 in., again at about the highest tunnel speed of 1.5 ft/sec, when the flow was perpendicular to the upper tip section. Karman Vortex is a vibration of a structure, caused by a shedding of vortices, such that the structure is excited into resonance when the shedding frequency equals the structural frequency. It was named By Dr. Theodore Von Karman, and has been identified by a range of Strouhal Frequency bands, see Ref. (2).

Model Vibration Tests

Two more models were made to help assess scaling and to aid in material properties such as mass and stiffness distribution and damping. These are shown in Fig.(3). While these models were being made, Dr. Ferman and his students calculated the full scale structural mass and stiffness and compared this with Dr. Monsey's design data-- a good comparison resulted. Model vibration was predicted, and then measured. The test data suggested simplifying the analytical vibration modeling(hurrah). In any event, the three models showed the following experimental data:

Model	Bending Parallel to tip	Bending Perpendicular to tip
Steel	35.8 Hz	40.5 Hz.
Copper	29.4 Hz	25.4 Hz
Plastic	9.49 Hz	8.25 Hz

Based on this data model scaling rules and analytical studies, the full scale frequencies were estimated to be 3.5 Hz for bending parallel to the upper tip, 4.5 Hz for bending perpendicular to the upper tip, and 13.5 Hz for torsional motion of the upper section, or tip region. Fig (4) is a sketch to aid in showing the models which were difficult to photograph.

Wind Tunnel Tests.

Wind Tunnel tests were run , and at the same time, loads were being calculated for both full scale and model size structure. This double effort was done to insure the aerodynamics in the full scale case were reasonable, since none of the past experience in Dr. Ferman's extensive background had dealt with helical structures. First, the plastic model showed only static deflections (of up to 1-1/2 in.) to 50 mph, and we were afraid to go to higher speeds. However, based on the water tunnel test, this should have oscillated from the Karman Vortex effect.

Hindsight now shows that we probably missed this effect which should have occurred at 15 mph, we simple missed it, as this is roughly the tunnel idle speed. Karman vortex effects are commonly only at a small band of speeds depending on which vibration mode excitation. The steel model showed no type of vibration or flutter for speeds up to 100 mph for air flow parallel to the upper tip, and again no excitation for a second run up o 78 mph for flow perpendicular to the tip. Static deflections were extremely small. We did measure the total drag load of 2.0 lb., close to predictions. The drag load scales to 12359 lb., we predicted a value 11000 to 12000 lb.. not too bad? The copper model was tested to 71 mph for wind flow parallel to the tip, and a static deflection of about 1/8-in. occurred. Likewise, Karman Vortex vibration was observed at speeds ranging from 43 to 56 mph with oscillation of up to 3/4 in. The drag load was measured to be 0.92 lb., again roughly the predicted value. This scales to 12877 lb. for the full size, in the predicted range again.

Full Scale Predictions

Static loads were predicted for model and full scale using the drag coefficients estimated by Dr. Andres. This was done for a wide range of wind orientation angles, and the shear mad moment diagrams were made for design checks. The drag loads correlated closely with Dr. Monsy's values as noted earlier. The root bending moment was found to be between 409,000 ft-lb. to 414,00 ft-lb., again close to Dr. Monsey's values.

Based on the wind tunnel models results and based on calculations, the Karman Vortex excitations of the full scale structure were estimated to occur in the speed range of 80 -180 mph, say an average of 130 mph, and with an amplitude some 5 ft at the upper tip. This is a mild vibration , with a slow build up, and thus would only cause serious problems for sustained winds of these extremes....and thus this is not very likely to happen. Similarly, flutter and divergence was computed for the models, and neither phenomenon was anticipated to occur in tunnel speed range, nor was any encountered. Thus the flutter and divergence for the full size is prediction is believed to be realistic. The analysis for the full-scale case suggests that flutter speeds and divergence speeds are similar, and believed to be in the range of 150-175 mph, a condition likely only in tornado conditions. The flutter would involve bending and torsion of largely the upper section only, and would be a mild type where build-up is gradual, requiring sustained winds of long periods, again unlikely.

The flutter methods used here was taken from Ferman's experience with this area from many years of Aerospace Industry and teaching, Ref. (3-4). The Equations of Motion used in the flutter analyses were:

$$\begin{bmatrix} b_0^2 M_{hh} & b_0 M_{h\alpha} \\ b_0 M_{\alpha h} & M_{\alpha\alpha} \end{bmatrix} \begin{Bmatrix} \ddot{q}_h \\ \ddot{q}_\alpha \end{Bmatrix} + \begin{bmatrix} b_0^2 \omega_h^2 M_{hh} & 0 \\ 0 & \omega_\alpha^2 M_{\alpha\alpha} \end{bmatrix} \begin{Bmatrix} q_h \\ q_\varepsilon \end{Bmatrix} = Q \begin{bmatrix} 0 & b_0 A_{h\alpha} \\ 0 & A_{\alpha\alpha} \end{bmatrix} \begin{Bmatrix} q_h \\ q_\alpha \end{Bmatrix}$$

where

$$M_{hh} = \int m\phi_h^2 dy\,,\ M_{h\alpha} = \int mr\phi_h\phi_\alpha dy\,,\ M_{\alpha\alpha} = \int I_{ea}\phi_h^2 dy$$

$A_{\alpha h} = -\int C_{L\alpha} C \phi_h \phi_\alpha dy$, $A_{\alpha\alpha} = \int C_{L\alpha} Ce \phi_\alpha^2 dy$

where m is the mass/span; I is the mass moment of inertia/span; r is the distance between cg and ea., positive when cg aft; e is the distance between the aero center and ea., pos. when ea. aft; C is the chord; $C_{L\alpha}$ is the lift curve slope; ϕ_h and ϕ_α are the bending and torsion mode shapes; and ω_h and ω_α are the bending and torsion frequencies, see Fig (5).

The flutter dynamic pressure is found from the equation:

$$\frac{Q_F}{Q_D} = \frac{1}{G^2}\left[B \pm \sqrt{B^2 - D}\right]$$

$$B = G(1+\Omega^2) - 2(1-\mu)\Omega^2$$

$$D = G^2\left[(1+\Omega^2)^2 - 4(1-\mu)\Omega^2\right]$$

$$G = \left[1 - \frac{(A_{h\alpha})(M_{h\alpha})}{(A_{\alpha\alpha})(M_{hh})}\right] \qquad \mu = \frac{M_{h\alpha}^2}{M_{hh} M_{\alpha\alpha}} \qquad \Omega = \frac{\omega_h}{\omega_\alpha}$$

$$Q_D = \frac{\omega_\alpha^2 M_{\alpha\alpha}}{A_{\alpha\alpha}}$$

The flutter frequency is found from the Equation:

$$\frac{\omega_F}{\omega_\alpha} = \sqrt{\frac{(1+\Omega^2) - G\dfrac{Q_F}{Q_D}}{2(1-\mu)}}$$

In this method, the lift is assumed to be in phase with pitching motion, but in reality there is a small phase angle. The phase difference is corrected by the Modulus of the Theodorsen Function, which adjusts the lift curve slope, and thus the flutter speed from the above equations is raised slightly from this effect. The reduced frequency, similar to the Strouhal number is the correlating index between these relations, see Ref (3-4).

CONCLUSIONS

This effort demonstrates that students and available equipment and testing facilities of a university can be combined with faculty experience to provide aid to industrial and community problems, as was done here.

The wind effects are still believed to be of a concern to keeping candles lit on all occasions, but generally for quiescent days, there will be no problem. Likewise, the interior temperatures will be acceptable for typical comfort index for most occasions.

The model testing and analysis related to the area of Karman Vortex, vibration, divergence and flutter is believed to be an a solid basis. We believe that the structure is sound under normal conditions and from typical storms. Tornadic winds might cause some minor problems, but this is believed to be unlikely as well.

We are pleased to have been of help in this venture, and would encourage more of our colleagues to engage in this type of community service. The structure and facility of the OLSNS has been on operation since Spring of 1998, and appears to be well on the way to long existence, see Fig (6).

REFERENCES

1. Andres, R.A., and Ferman, M.A., "Parks College Supports Engineering and Design of Our-Lady-of-the Snows National Shrine at Belleville, Illinios", 34th ASEE Conference, OSU, 14-16 April 1999

2. Den Hartog, J.P., " Mechanical Vibrations" Dover Book Co., 1984

3. Ferman, M. A., "Conceptual Flutter Analysis Techniques, Final Report for USN Contract N0w 66-0298-C," McDonnell Aircraft Company Report F322, 10 February 1968

4. Ferman, M.A., " Aeroelasticity Class Lecture Notes", Parks College of St. Louis University, MO., 1992

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BIOGRAPHIES

Dr. Richard Andres retired from Parks College in 1997, following 35 years of service, being named Prof. Emeritus at that time. He continues to teach and advise, part time, both Graduate and Undergraduate Classes. Dr. Andres holds two BS and two MS Degrees in Engineering, and a Ph.D. in Meterology from St. louis University. He is a recognized expert on Wind Tunnel

Design. He has designed and built several small airplanes, and is an endless source of knowledge for the model airplane builders at Parks College.

Dr. Marty Ferman joined Parks in 1992 following his retirement from the Former McDonnell Douglas Company where he worked for 34-1/2 years in Structural Dynamics. Dr. Ferman teaches a number of different courses at Parks, including Flutter and Aeroelasticity, and is a recognized expert in this field. He is a registered Professional Engineer, iwth Bs, MS and Ph.D. degrees in Enginnering, and is presently Director of Graduate Studies.

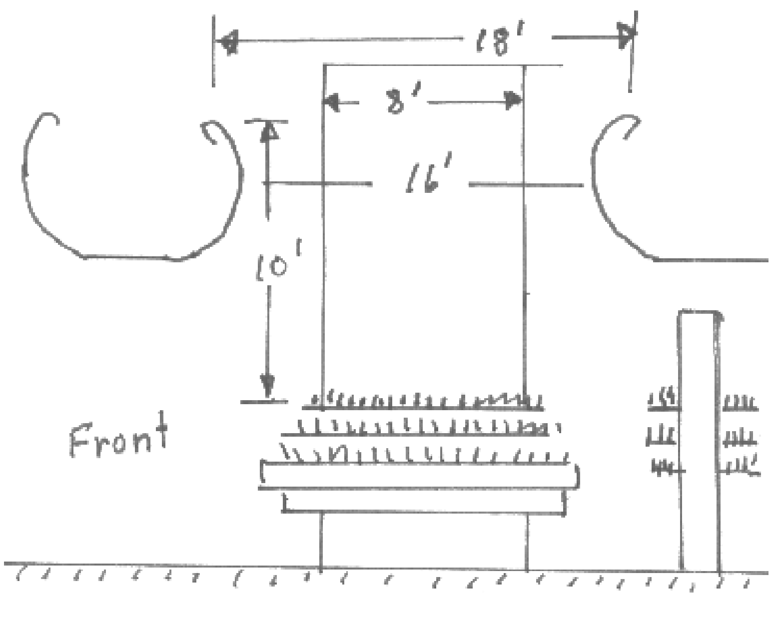

FIGURE 1 - OLSNS BUILDING

FIGURE 2 - FLOW VIZ MODEL IN WIND TUNNEL

FIGURE 3 - VIEW OF THE THREE FLUTTER MODELS
PLACED SIDE BY SIDE ON A TABLE

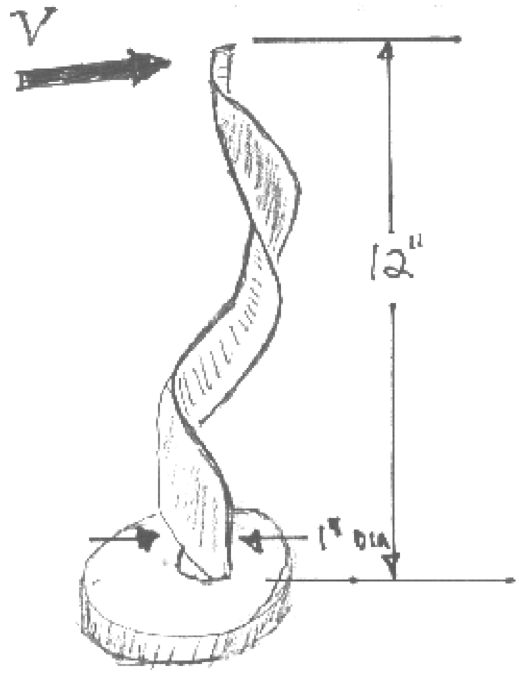

FIGURE 4 - SKETCH OF THE WIND TUNNEL FLUTTER MODELS

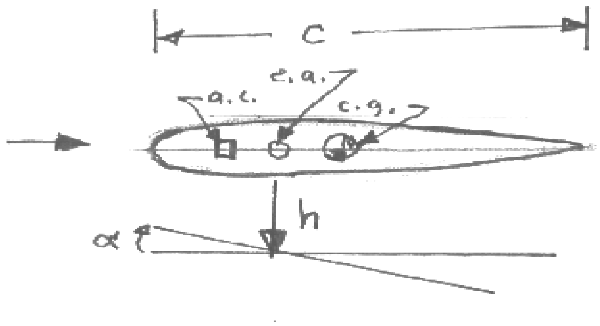

FIGURE 5 - FLUTTER MOTIONS AND
PARAMETER DESIGNATIONS

FIGURE 6 - VIEW OF THE COMPLETED OLSNS
BUILDING AND FLAMMA