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Reasons for Charles de Gaulle Airport Collapse

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Abstract: In the early morning hours of May 23, 2004, passengers in Terminal 2E at the Charles de Gaulle Airport in Paris partially collapsed resulting in several fatalities. Structural failure was caused by multiple reasons, all contributing to failure. Similar structures have been successfully erected and built around the world. One famous and comparable structure is the Berlin Main Railway Station. After investigations, it becomes clear that Charles de Gaulle Airport lacks suitable and effective geometry, which is present in Berlin Railway Station.

Key words: Charles de Gaulle airport collapse, structural failure, inadequate external reinforcement geometry.

1. Introduction

In the early morning hours of May 23, 2004, passengers in Terminal 2E at the Charles de Gaulle Airport [1] in Paris partially collapsed resulting in several fatalities.

The airport structure was an elliptical portal frame, made out of reinforced concrete and reinforced with steel tension struts.

Fig. 1 demonstrates the structural model of Charles de Gaulle airport. According to previously conducted accident research, the structure suffered from: lack of redundancy, inadequate or badly positioned reinforcing, steel support struts embedded too far into the concrete shell, weakened concrete shell support beams due to the passage of ventilation ducts shown in Fig. 2.

Similar elliptical portal frames have been successfully erected and built around the world. An example of similar structure can be found in Berlin Main Railway Station (Berlin Hauptbahnhof) shown in Fig. 3. The aim of this paper is to compare the similarities and differences between de Gaulle Airport and Berlin Main Railway Station externally reinforced elliptical portal frames.

Both structures are essentially designed for self-weight, wind load and minimum snow. Charles de Gaulle airport collapsed under its self-weight.

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2. Similarities and Differences between Charles de Gaulle Airport and Berlin Main Railway Station Externally Reinforced Elliptical Frames

Both Charles de Gaulle Airport (Figs. 1 and 2) and Berlin Main Railway Station [2] are externally reinforced with tension bars—tendons. Both structures are working elliptical frames with hinge support conditions. However, the structures look similar, but have substantial differences, which are listed in Table 1.

The elliptical frame in Charles de Gaulle Airport is shown in Fig. 1 from inside. The concrete precast elements form compressive side, illustrated with Point 1 in Fig. 4. Concrete is known to behave well under compression, but it has limited tensile or bending capacity without reinforcement. Concrete elements in Charles de Gaulle Airport were reinforced internally, but due to high bending moment, an additional external tensile reinforcement is used to form stronger cross-section, where concrete could carry mainly the compression and some secondary bending. Airport 2E terminal compression side was composed of precast wall and roof elements, which were casted on site to form a solid elliptical concrete

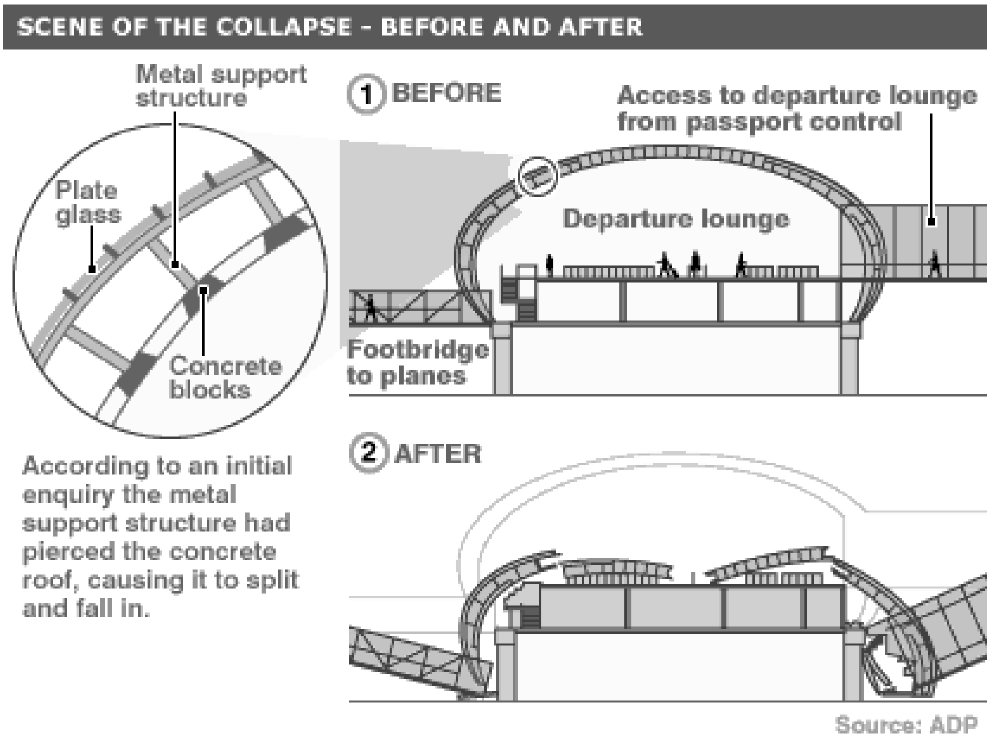

Fig. 1 Charles de Gaulle curved concrete shell reinforced with exterior steel struts.

Fig. 2 Partial collapse of Charles de Gaulle Airport on May 23, 2004.

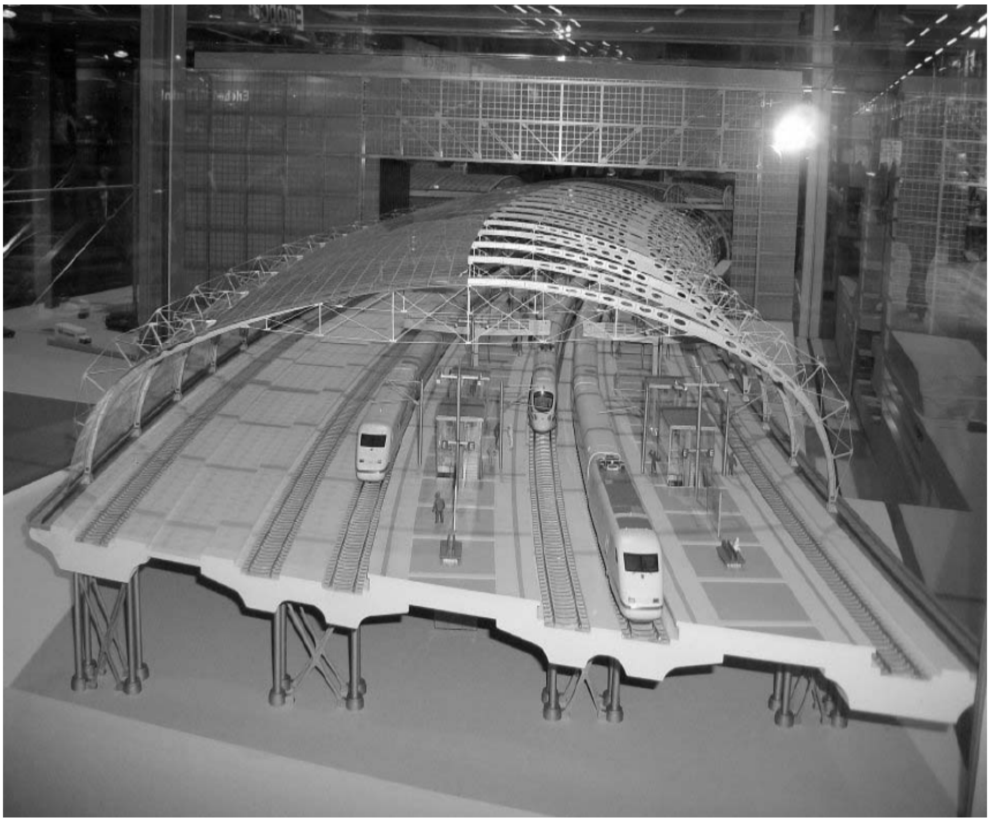

Fig. 3 Berlin Main Railway Station (Berlin Haupbahnhof).

Table 1 Similarities and differences between Charles de Gaulle and Berlin Main Railway Station.

Structural component		Charles de Gaulle Airport Terminal 2E	Berlin Main Railway
1	Compression side	Concrete	Steel
2	Tension side	Steel rods/missing reinforcement	Steel rods
3	Tension reinforcement geometry	External tension reinforcement does not follow tensile stresses of frames and passes through compressive side	External tension reinforcement follows the tensile side of the frame
4	Shear stiffness between tension-compression side	Missing/due to bending stiffness of compressive steel struts	Steel tension-only rods

compression strut in steel-concrete composite frame, as shown in Fig. 5.

External tensile reinforcement, shown in Fig. 4 (Point 2), does not follow the tensile side of frame. In the roof and upper part of the frame walls, the external tensile reinforcement should pass under the compressive side as is the case with Berlin Main Railway Station shown in Fig. 6. Due to the fact, that in case of Charles de Gaulle airport, the external reinforcement did not pass the most optimum location, which is the tensile side of frame moment, external reinforcement was rendered ineffective.

Charles de Gaulle Airport elliptical frame connection between tensile and compressive side also lacked clear shear stiffness, which in case of Berlin Main Railway Station is provided with tensile diagonals. Charles de Gaulle Airport relied either intentionally or unintentionally upon bending stiffness of tangential compressive rods as shown in Fig. 4 (Note 4).

These struts (Fig. 4, Note 4) were most likely not stiff enough to provide shear stiffness and lacked proper anchorage to concrete compressive side. It has been noted in previous investigations that some compressive struts had punched and sheared through the concrete slab. It is not surprising, giving the relatively thin concrete slabs and additional bending moment caused by shear force between tensile and compressive side.

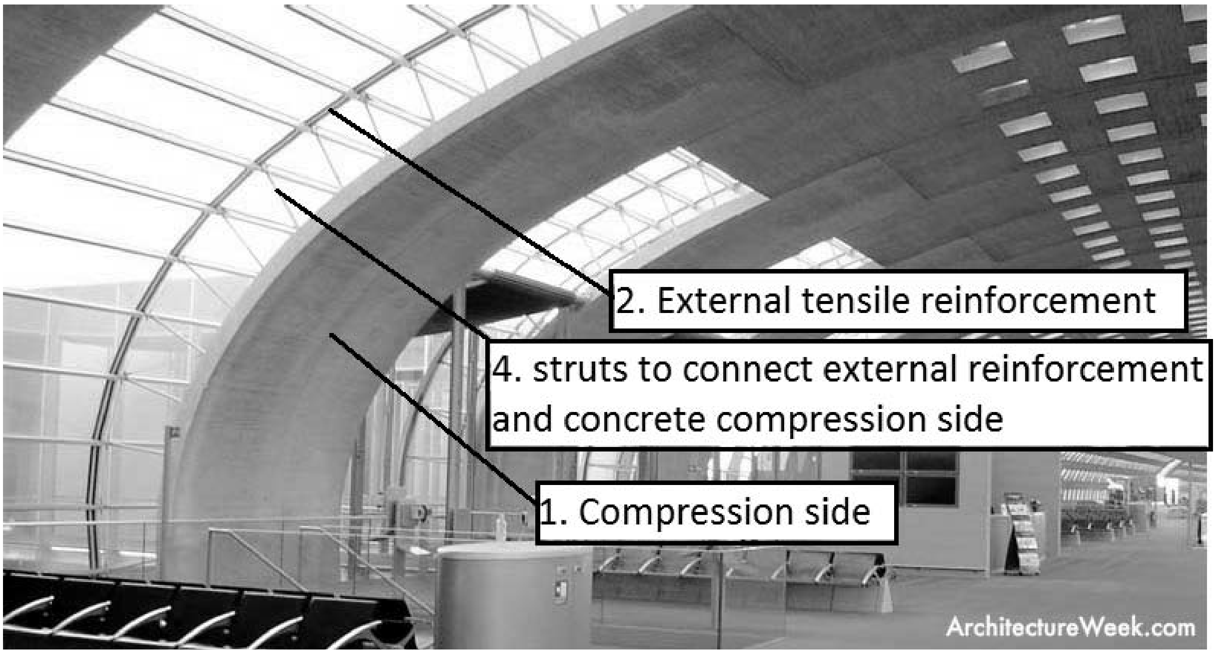

Fig. 4 Explanation of points shown in Table 1.

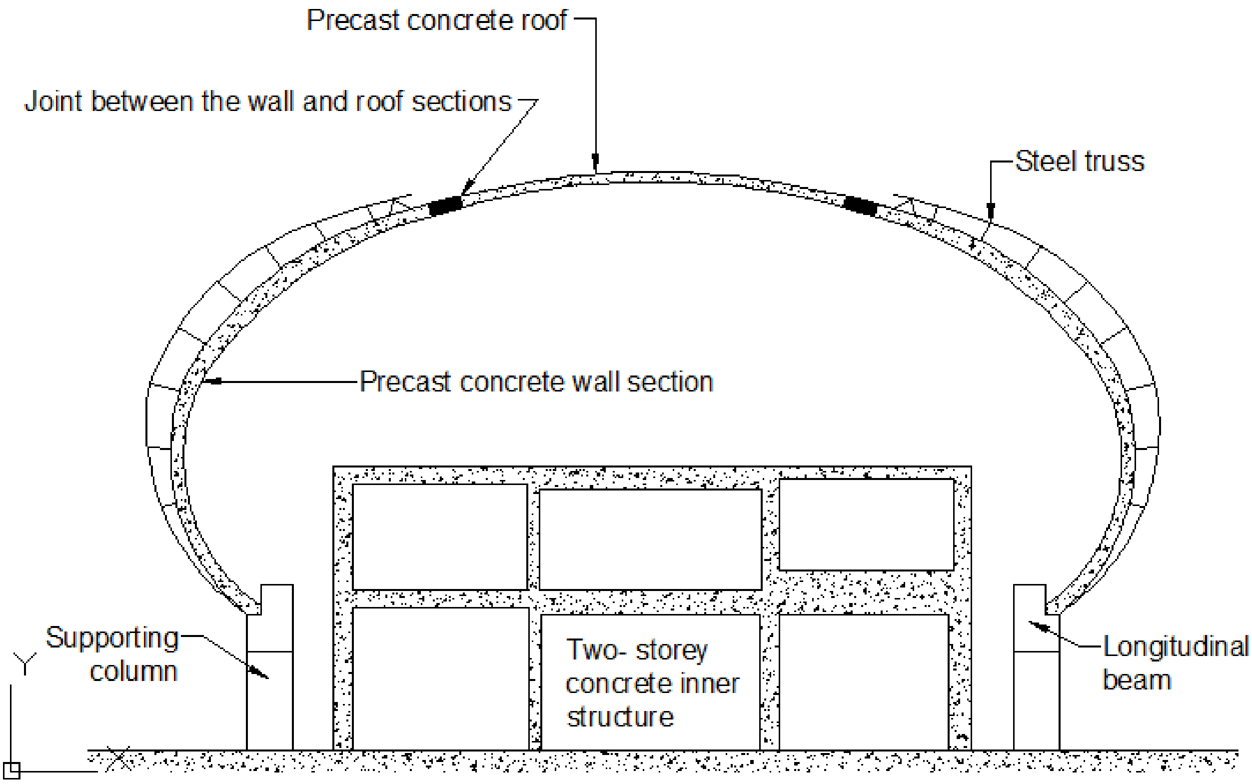

Fig. 5 Cast in place joint between roof and wall elements.

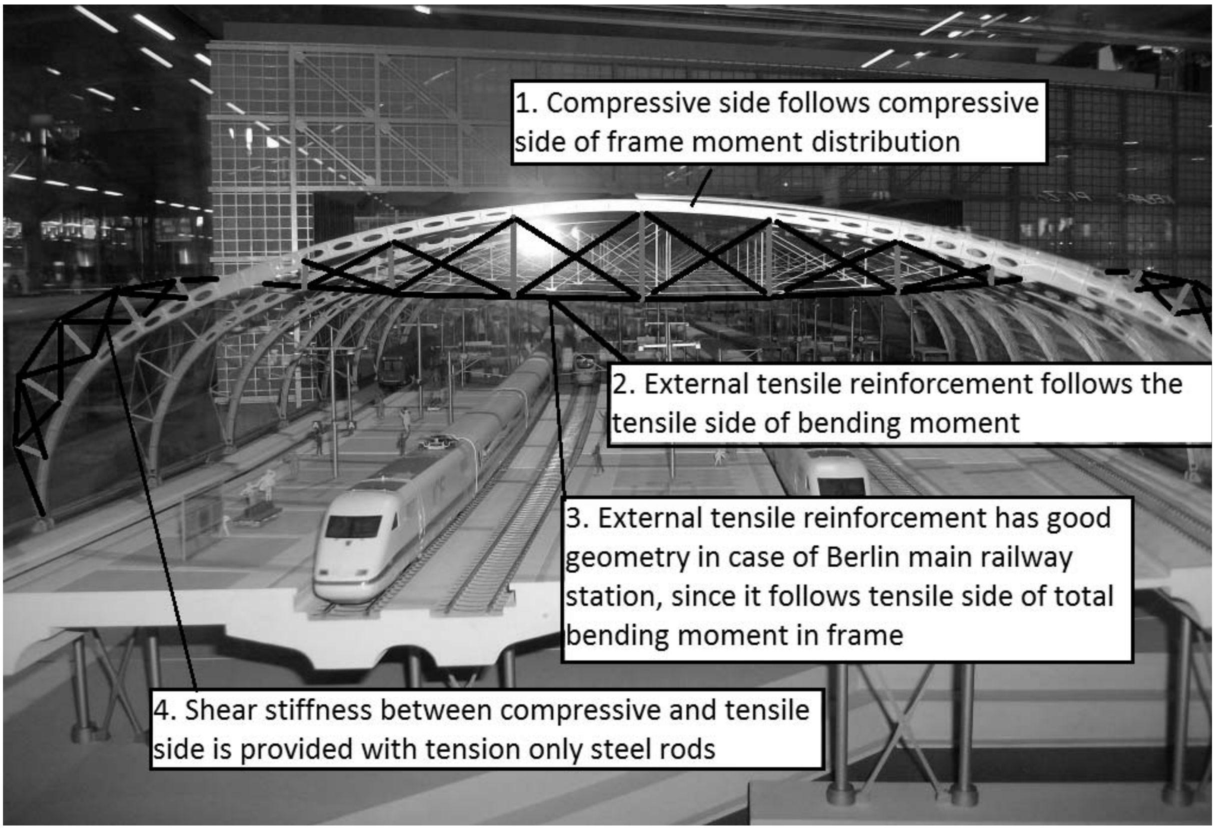

Fig. 6 Berlin Main Railway Tensile, compressive and shear struts arrangement.

Together with bad geometry of external reinforcement, the lack of proper shear stiffness between tensile and compressive side could be considered fatal and catastrophic.

However, even with bad geometry of reinforcement, the frame could work under large deformations, assuming that compressive failure does not occur on the compressive side. Assuming large deformations is not something practiced amongst conscious engineers. Large deformations are usually off the table for massive structures, due to excessive deformations and failure of materials.

While Berlin Main Railway compressive side is made out of massive steel section, Charles de Gaulle Airport Terminal 2E frame compressive side was made out of precast concrete elements. Both materials are well suited for such a task.

The substantial differences between these two structures are listed in Table 1 (Notes 2, 3 and 4).

Bad tensile side reinforcement placement, geometry and lack of shear stiffness and strength between tensile and compressive side rendered the tensile reinforcement virtually ineffective.

The concrete slabs in case of Charles de Gaulle Airport Terminal 2E had to carry their own weight without the benefit of external reinforcement.

Temperature changes were the final nail in the coffin of Charles de Gaulle Airport terminal.

3. Analytical Comparison between Externally Non-reinforced, Externally Reinforced with Inadequate Geometry and Externally Reinforced with Better Geometry

Here, a comparative numerical study between different external reinforcement layouts is performed using RFEM 5.04 [3] and conclusions are drawn. For comparison, a 2D frame shown in Figs. 7-9 are used. The frame has spacing of cc = 1.5 m and concrete shell thickness of h_{slab} = 250 mm. The concrete in analysis is C30/37 according to EN 1992-1-1 [4, 5].

The structure is loaded with self-weight only. The concrete density is γ = 25 kN/m^3. In Fig. 7, Case 1 is shown together with bending moment distribution and support reactions. In Fig. 8, Case 2 is shown, where Charles de Gaulle Airport external reinforcement is modeled. In Fig. 9, Case 3 is shown. In this case, an optimized geometry of external reinforcement is used. In all cases, the large deformation analysis is used. No shear stiffness is modeled between external tensile reinforcement and compressive side.

In Cases 2 and 3 (Figs. 8 and 9), the structure is reinforced externally with ϕ = 40 mm, with modulus of elasticity E = 210,000 MPa. Compressive struts connecting tensile and compressive side are CFRHS 150x8 structural tubes. Tubes connections to concrete are hinges and due to tension only rods in tensile reinforcement, no shear is transferred between compressive and tensile sides.

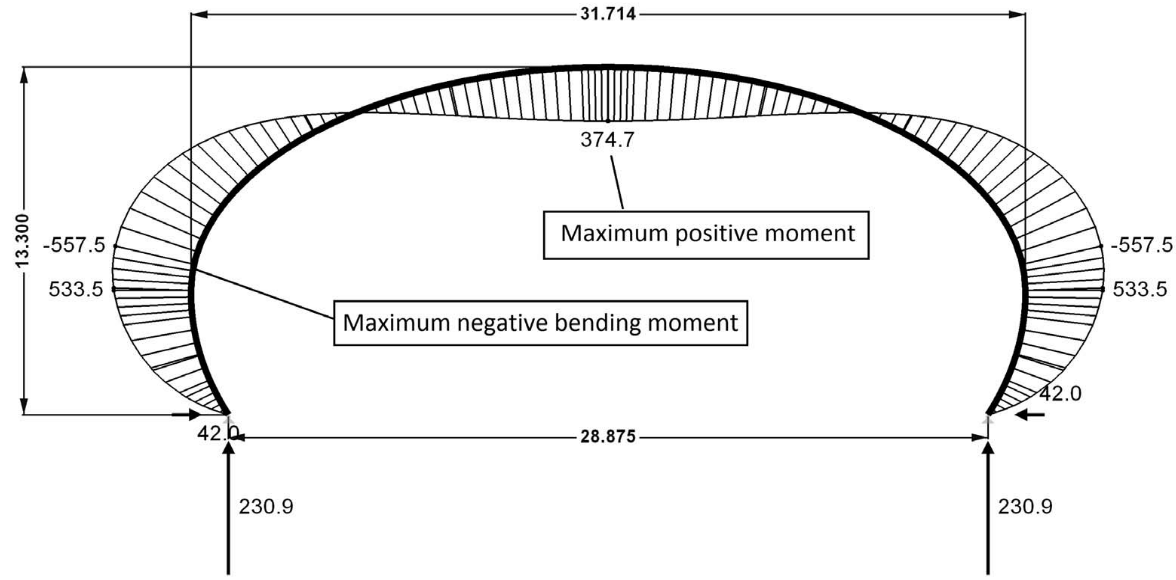

Fig. 7 Base frame geometry based on Charles de Gaulle Airport frame, bending moment distribution and support reactions due to self-weight.

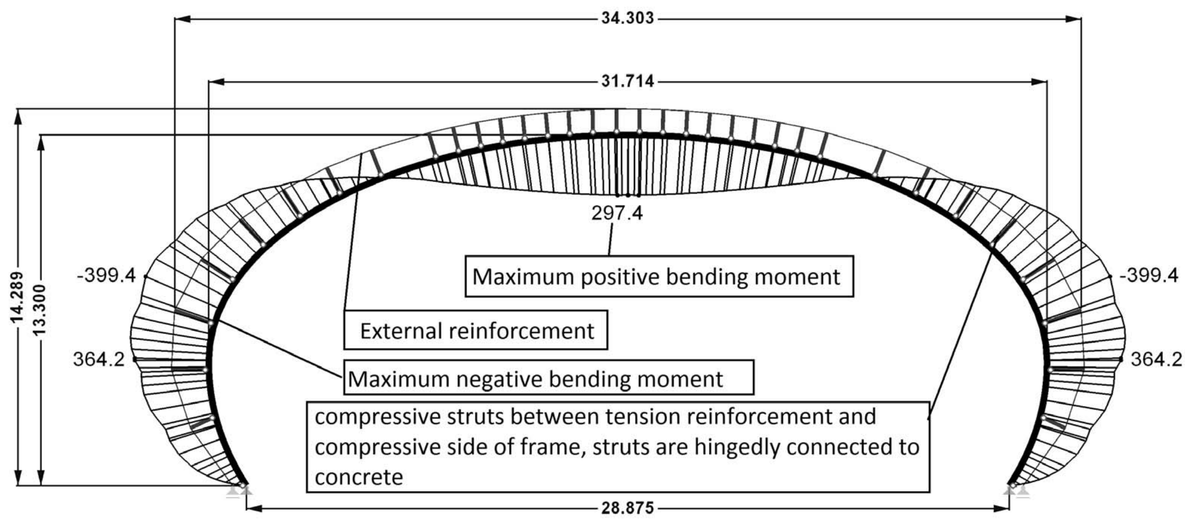

Fig. 8 Frame on Charles de Gaulle Airport with external tensile reinforcement, bending moment distribution due to self-weight.

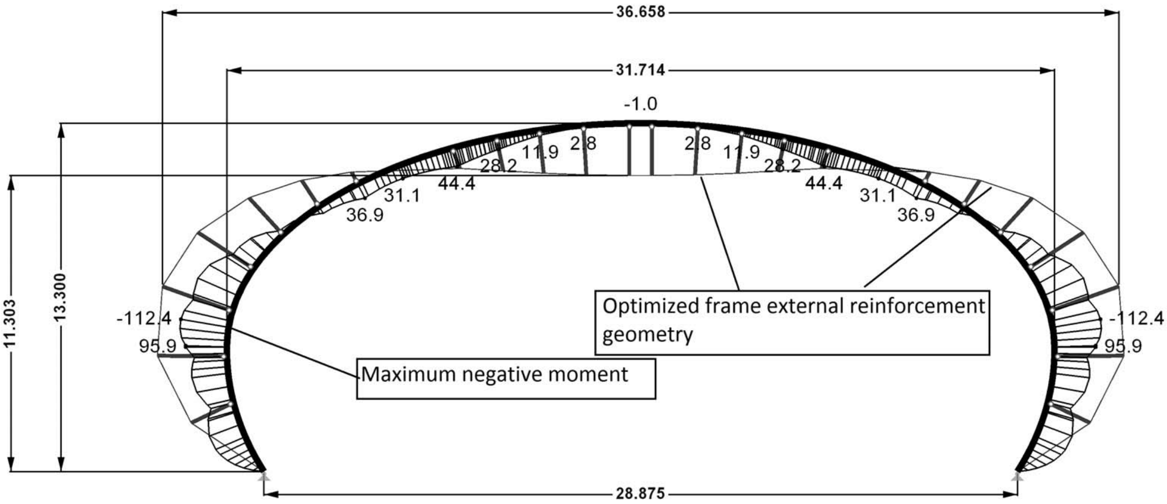

Fig. 9 Frame with optimized external tensile reinforcement, bending moment distribution due to self-weight.

Results of internal forces, maximum roof displacement, compressive and tensile stresses of three different cases are shown in Table 2.

Further, the structures with external reinforcement, Cases 2 and 3, were loaded with -10° in Celsius in the reinforcement parts which were outside the concrete frame. In Case 2, where Charles de Gaulle Airport Terminal 2E section was modeled, the whole tensile reinforcement is exposed to temperature change. In Case 3, only the parts supporting negative moments (in wall parts of the concrete) were loaded with temperature. Results are shown in Table 3.

For comparison, a fourth case (Case 4) is set up. In this case, the frame geometry is the same as in Case 2, shown in Fig. 8 (Charles de Gaulle Airport). The difference is in structural modeling assumptions. Struts between concrete and external reinforcement are rigidly connected to concrete and can therefore support some shear stiffness

Based on results shown in Tables 2-4, the following observations can be made:

- The structure is predominantly designed against bending moments;
- The suitable external reinforcement with good geometry can significantly reduce bending moments and hence stress levels (Case 3);
- External tensile reinforcement geometry in Charles de Gaulle Airport Terminal 2E (Case 2) had been ineffective and the reduction of stress levels as compared to plain concrete (Case 1) had been modest;
- Tensile stresses of plain concrete (Case 1) and ineffectively reinforced plain concrete (Case 2) far exceed characteristic mean tensile strength of concrete f_{cm} = 3.8 MPa < 24.3 MPa < 35.2 MPa. Hence, the concrete would crack and most likely suitable internal reinforcement would not be found;
- Given high tensile stresses in Case 2, one could conclude that the original Charles de Gaulle Airport structure was either assumed intentionally or unintentionally to have shear stiffness between external tensile reinforcement and concrete shell as shown in Fig. 10 and assumed in Case 4 in Table 4. Such stiffness could be assumed in analysis by modeling the compressive struts between external reinforcement and concrete to be rigidly connected to concrete shell. However, such an assumption would lead the tensile reinforcement on top of the roof in compression and totally ineffective. Secondly, struts would have to be designed for bending moments, which is caused by shear between concrete shell and external reinforcement. Bending moment in struts would make punching of concrete more likely. Even

Table 2 Deformations, internal forces, maximum compressive and tensile stress and average stresses due to normal force.

Structural system	Max deformation (mm)	Max negative bending moment (kNm)	Max compressive stress (MPa)	Max tensile stress (MPa)	Max axial compressive stress (MPa)
Case 1 (Fig. 7)	439.6	557.5	36.2	35.2	0.495
Case 2 (Fig. 8)	331.2	364	26.8	24.3	1.333
Case 3 (Fig. 9)	40.1	112.4	8.12	6.2	0.935

Table 3 Deformations, internal forces, maximum compressive and tensile stress and average stresses due to normal force with temperature loading and self-weight.

Structural system	Max deformation (mm)	Max negative bending moment (kNm)	Max compressive stress (MPa)	Max tensile stress (MPa)	Max axial compressive stress (MPa)
Case 2 (Fig. 8)	443	530.3	35.7	32.1	1.892
Case 3 (Fig. 9)	49.4	146	10.61	8.1	1.339

Table 4 Deformations, internal forces, maximum compressive and tensile stress and average stresses due to normal force with temperature loading and self-weight in Case 4 when maximum shear stiffness in between of tensile and compressive side is assumed due to bending stiffness of compressive struts CFRHS 150x8.

Structural system	Max deformation (mm)	Max negative bending moment (kNm)	Max compressive stress (MPa)	Max tensile stress (MPa)	Max axial compressive stress (MPa)	Von-Mises stresses in struts CFRHS 150x8 (MPa)
Case 4 (self-weight) (Fig. 10)	169.4	228.6	16.1	13.1	1.474	356.4
Case 4 (self-weight + temp)	218.4	299.6	21.2	17.1	2.04	481.4

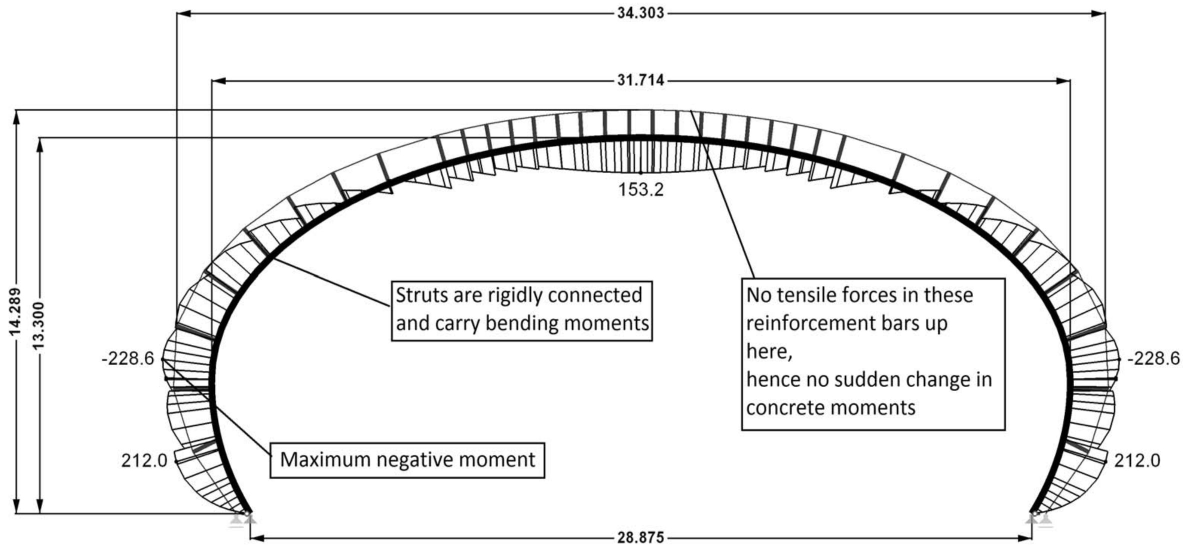

Fig. 10 Frame on Charles de Gaulle Airport with external tensile reinforcement, bending moment distribution due to self-weight. Struts are rigidly connected to concrete frame and hence tensile and compressive side work more like one single section.

with such assumption, the tensile stresses inside concrete far exceed mean tensile strength and hence cracking would be inevitable. f_{cm} = 3.8 MPa < 17.1 MPa (Table 4);

- Optimized external reinforcement geometry can lead to substantially reduced bending moments and hence stresses in structures. Optimally, chosen external reinforcement together with pre-stressing of tendon could lead to virtually zero or non-existent bending moment's level and can leave the concrete fully un-cracked under serviceability loads;

- Temperature change on -10 °C in steel rods could further degrade structural behavior in case of highly un-economical and inefficient choice of external reinforcement geometry as in case of Charles de Gaulle Airport Terminal 2E and lead to final failure, but failure itself cannot be blamed on temperature. The fundamental flaw in Charles de Gaulle Airport structure was the bad choice of external reinforcement geometry.

4. Conclusions

Based on numerical analysis of Charles de Gaulle Airport Terminal 2E geometry and photographic evidence, it is clear that the external reinforcement had been chosen based on appealing architecture, not based on solid engineering judgment. Ambitious geometry could not have been rigorously analyzed and designed, since the failed structure obviously had lacked important design aspects, like proper geometry and suitable shear stiffness

Similar externally reinforced curved frame had been successfully designed and built in Berlin Main Railway Station. This structure clearly demonstrates all the good design features for such frames. Berlin Main Railway Station has also redundancy due to clearly designed shear stiffness between external reinforcement and internal compressive frame allowing the external reinforcement—internal steel arch work like a composite member under un-symmetrical loading conditions and under extreme loading.

Charles de Gaule Airport Terminal 2E failed on locations, where concrete shells had been penetrated by passenger tunnels. Such penetrations worked like stress concentrators, but are not by themselves the reasons for collapse. Concrete structures, just like steel have redistribution capacity. With suitable and careful design, even opening among concrete shells are not catastrophic.

Independent of main compressive member material, steel or concrete, a good design is achievable. For tension members, steel is the suitable material.

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