THE APPARENT SETBACK TO THE IRON SKELETON SYSTEM OF CONSTRUCTION AFTER THE EXPERIENCE WITH THE CRYSTAL PALACE OF 1851

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For the modern observer, the Crystal Palace of 1851 in London appears to radiate a serenity as a symbol of progress towards the future. We have tended to idealise this structure so much, fitting it into our own preconceived notions, that its real attainments and problems are concealed by this myth. (1) This ingenious structure certainly played its part in the introduction of iron and glass into building construction; however, it was not brittle cast iron, but initially wrought iron and then steel which were to help the skeleton system of construction make its breakthrough. This may sound somewhat astonishing in view of the great popularity of cast pillars and façades in the last century. However, the differing behaviour of cast iron and wrought iron under strain, such as bending stress, thrust, torsion, tension and buckling, requires differing construction prodecures, about which one learns virtually nothing in the history of architecture, but without which it is not possible to produce a sensible system of skeleton construction.
The statement that the Crystal Palace was built entirely of glass and iron is incorrect. This misleading simplification was adopted uncritically from the layman's reports published everywhere. The exterior panelling was made up of wooden frames faced with decorative cast arches. On the ground floor level there was no glass at all, except at the entrances, just ventilation grilles and wooden shuttering. On the other hand, the upper storeys were 4/5 glazed, so that the proportion of glass in the total exterior surface area did at least amount to about 40 %. The partitions, the floors and the main girders of all single storey sections of the building and the vault arches of the great transept were all made of wood, as also were the transoms and gutters, for which Joseph Paxton had designed his much-quoted wood preparing machine. The Crystal Palace was thus not built in quite the same way as Victorian conservatories, let alone modern skeleton construction.
What is left then from this structure which could be relevant for us? There is, for instance, the complex organisation of the construction process which was to become decisive for the further development of building in general, (2) and also the constructive addidative unit of about 7.3 x 7.3 m. Each one sonsisted of four cast iron girders and trusses and could be stacked upwards and extended in area at will.

The idea of the three-dimensional addidative element is one of the most important aspects of this building from the technical-historical point of view. Thus, the Crystal Palace differs in its construction concept - if not also in detail - from all previous conservatory structures. It is important for the history of the development of both the architectural design and also of skeleton construction. The degree of inovation in Joseph Paxton's unit construction system was considerable. The hollow supports, for instance, were used both for draining off rain water, and, by adapting the cross section by means of varying wall thicknesses they were adjusted to the differing static stress. In this way it was possible to retain the external dimensions of the supports and thus guarantee the connecting geometry.
The early development of such modular units ranges from the prefabricated and standardised British houses of around 1830 down to the portable field hospital, the hotels and stores after the middle of the century. It is the structural modular unit of the Crystal Palace which represents a milestone in this series and not the steel skeleton or the glazed, suspended façade, which the Crystal Palace did not possess anyway.
The structural clarity which it was felt could be seen in this structure is a further fiction provoked by our present way of looking at the whole. It is, in fact, only due to the lack of time for planning. The structure of the Crystal Palace thus tends rather to represent a scheme than a carefully thought out system. In contrast to a normal design process, which has a simplification of the concept as its aim, it was Paxton's first rapid draft which was the simplest, and every further stage of design brought an increasing degree of lack of clarity. It was the great hurry in which everything was done and not the search for constructive clarity which led to the omission of irritating additions. When the building was then reerected three years later in Sydenham, and the original pressing time schedule was no longer important, other criteria came into play. Neither the simplicity of the structure nor the planning schedule now played any role. The Crystal Palace had, it is true, become an international symbol for industrial success, but its reconstruction in Sydenham was in fact the construction of a new building using the parts from the original building - the simple improvement was concealed. And yet, despite this, in the original Crystal Palace, the idea of the skeleton structure attained a clarity it had never had before, although the appropriate constructive solutions were still lacking. It was thus not possible for there to be a "setback" in the subsequent period, as the development described here had still not been carried out constructively. That may sound absurd at first, because the building was standing. But we shall soon see what a coincidence it was and how uncertainly it did stand.
The building site in Hyde Park was on a slight slope as was also the ground floor of the structure, albeit at a lesser angle. The ground floor, some 560 x 140 m in area, was designated as the zero level, and all heights were measured upwards and downwards from it, at a right angle to the sloping surface. As a result, not one of the pillars was vertical; there were also problems with the foundations. They all projected above the original ground level by the same amount, but at the same time, their distance from the ground floor surface level differed each time. The cast-iron base pieces were thus all of differing lengths. They had to be measured out on the spot and manufactured individually. (3) This, of course, completely contradicted the principle of prefabrication in series, in which the aim is the manufacture of as many components of the same size as possible. We know that there were only six weeks available for detailed planning. It was simply not possible to deal with all new individual problems occurring correctly on the spur of the moment.
No prefabrication industry developed as a result of this, although the Crystal Palace had great success as a building and was copied in a number of further exhibition buildings. Even at that time, it is possible to observe a desire for a renewal in architecture. A year before Paxton's sketch project in 1849, the director of the Belgian industry museum was pleading for a new architecture using glass and iron. (4) Gottfried Semper and other architects proposed the use of the new construction materials. However, their desire was just for a stylistic change and not for a structural one.
However, the building concept which found its expression in the Crystal Palace can be better compared with the "balloon frame" method

of construction used in North America than with the modern skeleton form of construction. The "balloon frame" from the American pioneer period consisted of a construction unit component of pre-cut wooden parts with standardised cross sections which were assembled to form a frame using simple nailed joints. The bracing for the construction came from the diagonal board covering which was nailed directly to the frame.(5) The construction technology was simple enough in this case, so that the "balloon frame" system of construction was able to spread rapidly. In contrast to this, the absence of any development of a prefabrication industry as a consequence of the construction of the Crystal Palace was due to constructional problems.

Joining together the cast-iron parts was a considerable problem. If the Ironbridge of 1779 was still able to derive its joint geometry and method from wooden constructional methods, the Crystal Palace for its part already for the most part had its models in machine engineering. The design of the joints and stiffening flanges was already well developed. The modular unit was apparently understood as a stiff frame construction - such as we know in modern steel construction. Charles Cowper wrote the following about this in 1852: "One of the principal constructive characteristics ... is the form of the supports or framework which has two functions to fulfil. The first and primary function of the supports is to support the roof; the second and equally important function is, however, the side trussing of the whole structure." (6) We can here observe the idea of a construction system, namely that of the bending-resistant storey frame, which it was not possible to construct in cast iron at that time. The connecting flanges were too brittle and the supports were only capable of bearing slight transverse forces. Everything had to be additionally braced and considerably over-dimensioned.

The planning committee discussed at length whether the transverse bracing of the wedged frames and of some less diagonal trusses would be enough: because at that time it was still only possible to take an intuitive approach to the stability question of purely skeleton structures. Professor George Airy, the Astronomer Royal, was in 1850 originally opposed to the construction of the Crystal Palace because he regarded it as being inadequately braced. To illustrate his opinion, he quoted the example of the factory buildings from the close of the eighteenth century, the load-carrying system of which were, it was true, made of iron, but which were surrounded by solid walls around the outside to assure their rigidity. Was Professor Airy wrong?

Robert Mallet informs us that many more diagonal trusses were incorporated into the structure of the Crystal Palace than had been originally envisaged and continues: "The building was taken down and has been reerected at Sydenham in a manner greatly to increase its stability, as regards the greater part of the structure at least ... And yet, nevertheless, a very large wing of the Crystal Palace has been actually blown down in the interval - that portion of the whole that probably more accurately represents the structure of the building as it stood in 1851 ..." (7)

In 1851, the building remained standing, despite the winds, and in particular, despite the thermic expansion of the iron. The joints between the girders and trusses were keyed partially with wrought-iron wedges and partially with oak ones. The wooden wedges were also intended to allow a certain degree of expansion, (8) something which proved, however, to be illusory. In fact, the building behaved like a long, solid iron girder. As the great wooden arches of the transept were not braced, there was an effective transverse joint in the middle of the building. The two largest continuous roof surfaces were thus approximately 22 m wide and 260 m long. Mallet's description shows how closely the building escaped collapse: "We ourselves, however, had an opportunity, during the early afternoon of one of the hottest days of the summer of 1851, of examining with some accuracy the effects of expansion by solar heat upon the frame of the building: and we can testify to this as a fact, that at the extreme western end, and at the fronts of the nave galleries, where they had been the longest and the most heated, the columns were actually about two inches out of plumb in the first range in height only ... As we gazed up at these west-end galleries densely crowded with people, and over the ample spread of the nave equally thronged, and thought of the prodigious cross-strains that were at that moment in unseen play in the brittle stilting of the cast-iron fabric, we certainly felt that 'ignorance was bliss'". (9)

The idea of skeleton construction was, apparently, far ahead of the technical possibilities of the time. Detail solutions were developed at that time, in particular as part of the tasks of the then new profession of civil engineer. The engineers attempted to understand the behaviour of the new construction material from the technological and material-technological aspect.

Cast iron was well-suited to take compressive forces, but not tensile forces and bending loads. The Ironbridge of 1779 had introduced the use of cast iron as a construction material. So long as arched bridges were built, only compressive forces had to be coped with. As attempts were made to build girder bridges, which were particularly subject to bending forces, they tended to collapse again under relatively slight loads. The truss beams in the Crystal Palace were only able to withstand the loads because they were increased in height to about 1/8th of the span, or 90 cm, to produce the presumed additionally braced corner joints. The construction of the Britannia Bridge and Conway Bridge in North Wales in 1850 brought the decisive change. A team consisting of a railway engineer, a shipwright and boiler manufacturer, a mathematician and a material-technologist developed a wrought-iron girder construction. The experience with the new material came from ship construction.

Then, in Continental Europe, the solid side construction began to be replaced by lattice girders in order to economise in the use of expensive iron. In 1857, the great Vistula bridge at Dirschau was constructed, and in 1862, the first genuine truss girder bridge near Grandfey in the Swiss canton of Fribourg. The graphic static methods of calculation which were to prove decisive for this development were produced under the direction of Karl Culmann, who taught them from 1859 on in his lectures at the Federal Polytechnic in Zürich. Solutions to the various constructional problems which had previously bedevilled the construction of the Crystal Palace, began to be found in civil engineering.

The construction of the exhibition hall in Paris in 1855 brought further experience. Mallet wrote: "Accordingly, in the Palais de l'Industrie, M. Barrault tells us that they were useless, and that under the bright sun of Paris the expansion of his building was sufficient to break glass and produce leakage; although structurally his building was incomparably better designed to break up into short lengths the expandable iron frame, every-where but along the length of the three great parallel roofs". (10)

As work began about 1860 on the designs for the second London world exhibition in 1862, the designers were, for the most part, aware of the construction problems. But appropriate solutions had still not been developed. How would it be possible to combine representative structure, rigidity, water-proofness, great spans, small pillar cross sections and planning freedom in the interior with one another? The answer was readily to hand: the successful modular system in iron combined with a solid, wind-resistant stone exterior. Mallet also supported Barrault's proposal to introduce expansion joints at regular intervals. However, contrary to Barrault, he felt that the structure would have to be supported by a solid self-supporting wall, on the one hand to guarantee rigidity, and on the other to protect the iron structure from excessive warmth.

This apparent retrograde step from a purely skeleton structure with a non-bearing external wall to a skeleton with a bracing envelope means that only the real innovation, namely the additive, space-constructional modular system was adopted, and not the unsolved weaknesses in the system as well. But it was by no means certain that the final form of the system would mean a light, non-bearing exterior facing. The development could equally well have led to a bracing exterior. Because if the so-called "pure" system with its non-bearing exterior facing is analysed, it is possible to see how extravagant it is in reality. The latest developments in skeleton construction seem nowadays to be moving towards the bracing exterior facing: we only need to think of the example of the external bracing of the Hancock Tower in Chicago. In our evaluation, we should not allow ourselves to be distracted by the lightness or heaviness of the façade construction material, but should only observe the system: Does it brace, or not? Does it bear, or not?

The system as applied in the Crystal Palace in 1851 was unsuitable with its use of cast iron, although it was like a rigid frame construction. In principle, it was unstable, and only stayed standing thanks to fortuitous circumstances. The picture presented to us is thus confusing. It is not something modern which we are encountering here, but a formal premonition of one of many types of structure which would later be possible.

Whether this should be taken as a stroke of genius, a premature of temporarily unsuccessful attempt, depends on the point of view adopted when making the observation. The construction of the Crystal Palace demonstrated clear characteristics of all three possibilities. But the real achievement in the case of the constructive realisation of the steel skeleton system took place in the form of much smaller, more anonymous steps. This history has still to be researched.

Notes

1. Siegfried Giedion: Time, Space and Architecture, the growth of a new tradition. 1941 Cambridge (Mass.);Harvard University Press. 5th Ed. 1974, pp. 249.255.
2. Tom F. Peters: Time is Money. Die Entwicklung des modernen Bauwesens. 1981 Stuttgart: Julius Hoffmann, pp. 159-183.
3. Charles Cowper: The Building Erected in Hyde Park for the Great Exhibition of the Works of Industry of All Nations 1851. 1852 London: John Weale, p.iv.
   also: Charles Fowler Jr.: The Crystal Palace Building.Series of nine instalments in: The Illustrated Exhibitor. no date (1851) London: John Cassell. p. 80.
4. Peter Collins: Concrete. The Vision of a New Architecture.A Study of Auguste Perret and his precursors. 1959 London:Faber & Faber,p. 114.
5. Daniel Boorstin: The Americans. 2nd Ed. 1969 Harmondsworth: Penguin Books. Vol. I., pp. 193-196.

   This Method of construction was also made popular in the history of architecture by: Siegfried Giedion: op.cit.,p. 346-354.
6. Charles Cowper: op.cit., p. 2.
7. Robert Mallet: The Record of the International Exhibition 1862. No date (1862) Glasgow, Edinburgh, London: William Mackenzie,p.60.
8. Charles Cowper: op.cit., p. 6.
9. Robert Mallet: op.cit., p. 59.
10. ibid. p. 59.