Chapter 5:

IRON AND STEEL

DEFINITIONS:

There are three primary varieties of iron based materials that have been used in buildings over the past several centuries: wrought iron, cast iron and steel. Although similar in appearance, each has distinct structural properties which greatly affect their tensile capabilities, construction methodology and architectural applications.

Wrought iron was the earliest form of the material used in buildings. Iron would have been mined and the material heated over fires until malleable, then hammered into desired shapes. The appearance of the material was very rustic, and its earliest applications employed the material as a reinforcing for stone as it had very good tensile properties.

Cast iron was developed when higher heat was possible in forges. The iron was able to be heated to a liquid state and poured into moulds. This greatly enhanced the appearance of the material and allowed it to be mass produced as columns, trusses and railings (for instance). The production process resulted in product which was significantly more brittle than wrought iron, which limited the spanning distances of cast material.

Pig iron is the iron produced by the reduction of iron ore in the blast furnace.

Steel was developed during the mid 1800's and uses a process which heats without creating a brittle product, and which allows for the addition of alloys which modify the structural properties of steel. As a result, steel is far superior in tension than wrought iron, and makes optimum use of its structural assets when designed for pure tension situations. Steel is an iron base alloy, malleable in some temperature range as initially cast, containing manganese, usually carbon, and often other alloying elements. In carbon steel and low alloy steel, the maximum carbon is about 2.0%; in high alloy steel about 2.5%. The dividing line between high and low alloy steels is generally regarded as being about 5% metallic alloying elements. Steel is to be differentiated from two general classes of 'irons': the cast iron on the high carbon side, and the relatively pure irons, on the low carbon side.

ORIGINS OF IRON IN ARCHITECTURE:

The structural use of iron in building dates back to antiquity. The Greeks first used wrought iron beams to reinforce the entablatures of their temples. Iron was rarely used in great quantities before the 18th century because of low rate of production, difficulty of shaping large members, and great cost. From the 14th to the 18th century it was produced in a blast furnace, which had an opening at the top through which iron ore and charcoal were periodically fed, and into which air was blown with a water operated bellows to raise the heat level. Because of the nature of charcoal there was a limit as to how much could be introduced into the furnace at a time and hence a limit on the size of the furnace and the resulting production. There was a fear of completely depleting the forests of Europe to supply charcoal, and the heat produced by this method was insufficient to yield the maximum fluidity of iron, a condition necessary for the highest quality of cast iron. A high heat was required to change the iron into a sufficiently molten state facilitating the flow of the material into the intricately designed moulds.

Wrought iron had been fabricated for centuries, at great expense. Time consuming and strenuous process of forging the ore with water driven hammers at a maximum of 40 horsepower produced only a ton of iron every 12 hours.

The industrialization of the production of cast iron was invented by Abraham Darby in Shropshire in 1709, by substituting coke for charcoal as fuel. This provided greater heat as the fuel could be shovelled into the ovens in greater quantities ... therefore, larger ovens and more production.

The quality of coke smelted iron was inferior to the charcoal produced material due to the presence of phosphorous in the coke. Remelting helped rid the iron of some of the impurities, but the iron still remained brittle.

John Wilkinson invented the steam engine in 1776 which could operate the blowers of the furnace. The higher temperature allowed for a more fluid product and higher quality cast iron. He also adapted the steam engine to operate the forge hammer, improving the wrought iron production.

Henry Cort improved the rollers in 1780, and invented grooved rollers which would cut the iron into bars. He also invented puddling, whereby the pig iron was stirred and more oxygen came into contact with the material making it more malleable. These methods not used in France until 1818.

EARLY FRENCH EXAMPLES OF IRON USE:

Claude Perrault pioneered the use of iron reinforcement in the design of the colonnade of the Louvre (1667-74). He inserted three iron bars of 5 cm. diameter joined end to end vertically, extending from the base to the capital. The Architrave, spanning 16.5 meters between each set of paired columns. The flat voussoirs were joined with z bars.

The use of iron tie rods and cramps in Place de la Concorde, Paris. Designed by Ange-Jacques Gabriel in 1763. The design for the building resembles the Louvre colonnade by Claude Perrault.

Jacques Germain Soufflot; Ste. Genevieve (The Pantheon) 1776. Jean Baptiste Rondelet assisted Soufflot in the design of wrought iron reinforcing to aid in containing the thrusts of the dome. Soufflot investigated numerous possibilities for the dome, including two and three shell versions. The two shell version was used, but still required a significant amount of iron reinforcing to contain the thrust, prevent bursting, and channel the loads into the stone piers. These were significantly reduced in size from previous church dome support designs. Nonetheless, the structure has suffered significant cracking and is currently undergoing restoration and repair to correct severe structural faults.

Victor Louis; Theatre Francois, 1786: pre revolution use of iron--used in roofs on theatres and passages (arcades) even though the cost was very high; illustrates use of Ango beam, which was invented in 1785 .

August Renard (1744-1807). Iron roof over Salon adjoining the Grand Galleria, Louvre, Paris. 1789: temporary solution to house the collection of paintings at the Louvre. To provide overhead lighting by skylight. Had the form of an ogival groin vault with a 14.6 meter span, supporting a 5.2 meter wide skylight of 240 panes of glass.

NAPOLEON AND THE EFFECTS OF THE REVOLUTION ON THE IRON INDUSTRY:

The Revolution brought a halt to building. Although England was making significant contributions to the development of iron structures in the way of bridges and railway structures, politics prevented intercourse with England so the French could not learn from the English. Napoleon encouraged the iron industry, holding expositions of iron technology in 1801, 1802 and 1806. He also supported the newly formed engineering schools such as the Ecole Polytechnique (where J.N.L. Durand and J.B. Rondelet were teaching). Napoleon was interested in iron for its use in weapons and monuments. He would only grant authorization for new forges if they were to use coke rather than charcoal (modernization). This is tied to his preference for cast to wrought iron, as it was more suitable for the products he desired and he was concerned about the depletion of the French forests.

Delon de Cesart et Dillon. Pont des Arts, Paris, 1803: is a footbridge spanning the Seine in nine arches resting on stone piers 18.1 meters apart. Each arch is composed of 5 principal ribs 1.8 meters apart, supported on skewbacks. The ribs, which are of rectangular section, 16 centimeters thick are in two parts, joined at the summit. The principal ribs are reinforced by additional ribs, which radiate above each of the masonry piers to connect one major rib to another. Cast iron ties join the ribs together transversely, and struts connect the small arches to the principal arches. Prior to the adoption of iron for bridges, timber had been employed. Timber is better in tension than compression, and the fallacy of the early cast iron bridge design is that it imitated timber construction subjecting the members to tension -- not recognizing that a different approach should be invented which would subject the members to compression.

Louis Bruyere. Pont sur la Crou. Saint Denis, 1808

Resistance to fire was the major reason for the spreading interest in iron construction. Industrialization of manufacturing during the latter 1700's effected the construction of numerous multi-storey mill buildings. These were typically constructed of solid masonry bearing walls, with small punched windows, and an interior structure of heavy timber columns and timber floors. Because of the weight of the equipment and associated storage of materials, the bay sizes for the timber structure were often as little as 7 to 10 feet on centre. The density of the structure, coupled with problems of spontaneous combustion, made iron a very favorable alternate material.

Francois Belanger. Dome of the Halles au Ble. 1807-11: competition for the design of the dome to replace the former timber one which had been by fire in 1802. Cost 700,000 francs, seven times the original cost estimate. Based on the voissoir principle as proposed by Philibert De l'orme. Composed of 51 arched meridians each in 5 sections, or voussoirs, joined end to end, and decreasing in depth toward the summit. Each voussoir resembles a short beam, with upper and lower ribs joined at several points along the web. Supported on a circular cast iron wall plate. The base of the ribs are 2.42 meters apart and are fastened to the stone piers by anchor bolts. The diameter of the dome is 39.26 meters. A compression ring of 11.25 meters diameter at the summit supports a lantern. The solution proved durable, and the building is used today as the "Bourse" or stock exchange.

Passages des Princes. Paris, 1860: Initial idea to access dense urban fabric. Glass covered streets. A few built under Napoleon in the early 1800's, many in the 1820's. By the mid century the designs had progressed to ensure ideas of marketting and merchandising. Sometimes three stories but never more. Cast iron used for its decorative properties.

Travernier. Gallerie de Fer. 1829: precursor to modern shopping center. Different from the passage in that it provided a multiple shopping experience in a single structure, however, the shops separately owned and run.

ADVANCEMENTS IN THE USE OF CAST IRON DURING THE EARLY 1800'S:

Henri Labrouste: (1801 - 1875)

Pompeii. Discoveries of Polychromy that affected the design and study at the Ecole des Beaux Arts. Henri Labrouste's "Agrigentium 1928" watercolour was done in the style of the Beaux Arts while studying in Italy. Henri Labrouste's "Temple of Hera" at Paestum, restoration was done during his Fourth year envoie. 1828-9.

Henri Labrouste project "Cour de Cassation", 1824. Rendered elevation and long section, and section through main courtroom. Won the Grand Prix of Rome in 1824. Studied at Ecole des Beaux Arts. Inspired by the work of Hittorf in the arguments of polychromy, was one of the first to argue that such structures had been brightly coloured. Insisted on the primacy of structure and the derivation of all ornament from construction.

It is interesting to consider a reflection and comparison with the plans of Durand who was teaching at the time at the Ecole Polytechnique. Durand proposed the "Mecanisme de la composition" which was a grid methodology upon which to place building elements such as columns and walls. Both the grid and the Beaux Arts style which observed classical symmetry and order in the planning of buildings, permitted the effective adoption of cast iron into the building as it required repetition in the design in order to achieve economy.

Henri Labrouste: Biblioteque Ste. Genevieve 1838-50:

Henri Labrouste. Biblioteque St'e. Genevieve. 1838-50: Plans, elevation, cross section. Inspired by the author Victor Hugo who wrote on architecture in the first half of the 1800's. He argued "Ceci tuera cela", this will kill that, the printing press of architecture. Of the book "Notre Dame de Paris", Labrouste was a critic. Formed his own atelier in 1830 when he arrived back from Rome. The library was created to house part of the library impounded by the French state in 1789. Consists of a perimeter wall of books enclosing a rectalinear space and supporting an iron framed, barrel vaulted roof which is divided into two halves and further supported in the centre of the space by a line of iron columns. Style called Structural Rationalism.

There are 19 regularly spaced arches. Only the upper portion is glazed, allowing light to penetrate the second storey reading room, measuring 17 by 80.75 meters.

Henri Labrouste: Biblioteque National 1857-67:

Inserted in the courtyard of the Palais Mazarin, consists of a reading room covered by an iron and glass roof carried on 16 12 inch diameter cast iron columns and a multi storey wrought and cast iron book stack. The reading room is top lit as well as the stacks, the light filtering down through iron landings to the bottom floor. The nine identical domes are 10.5 meters in diameter. Columns are 10 meters high. Columns are joined by wrought iron arches built up of plates and angles. The skeleton of each dome is composed of a series of arched wrought iron meridians in T sections, joined by concentric circumferential ribs. White enameled fill the spaces between the metal tracery. Unusual as it exposed iron as a material in a permanent public building.

THE INVENTION OF STEEL AND ITS EFFECTS ON DESIGN:

The invention of the Bessemer converter in 1867 allowed for the use of some steel in this building. This is a process for making steel by blowing air through molten pig iron contained in a suitable vessel, and thus causing rapid oxidation mainly of silicon and carbon.

Jules Saulnier: Menier Chocolate Factory, Noisiel, Seine Et Marne, 1871-2:

One of the first multi storey metal framed buildings in the world. Building is superimposed over three turbine generators set into the river. The lightweight structure rests on the abutments of the sluice gates which take the form of masonry piers. Structure composed of two exterior lattice girders running the full height of the building, and two rows of cast iron columns running down the interior volume on either side of a central corridor. Both the lattice girders and columns were supported on riveted, sheet iron, tubular box beams spanning between the masonry piers. Intermediate floors were formed by brick vaulted construction spanning onto riveted wrought iron joists which in their turn were carried by the external alttice girders and the internal columns. Exterior lattice infilled with hollow brickwork.

Eugene Emmanuel Viollet-Le-Duc (1814-79):

Eugene Viollet-le-Duc, Project for an Hotel de Ville: "had the mediaevil builders possessed cast or rolled iron of considerable dimensions, they would not have employed such a material as they employed stone ... They would, on the contrary, have sought contrivances more in harmony with the nature of metal." Felt it was not logical to use iron alone to construct buildings as masonry is a much better insulator--need to find a way to combine the two, employing each to its own properties, each fulfilling a separate function. Felt that the disguising of the true materials of the structure had brought moral degptlr-r@tion to the architecture of his time.

Viollet-le-Duc. Unpretentious Shop and Apartment Building.

Alphonse Gosset. Moet et Chandon Wine Establishment, Epernay. c. 1879.

EXHIBITION BUILDINGS: GROUNDS FOR EXPERIMENTATION

Sir Joseph Paxton (1803-65):

The New Victoria Regia House designed for the Duke of Devonshire at Chatsworth. Paxton based the design of iron and glass upon the structure of the leaf of a giant lily pad.

The Crystal Palace, 1851. Paxton was a late, specially requested entry for the competition for this building. Its form, materiality and detailing arose out of very special conditions for its building. It had to be designed and constructed within 6 months, and be able to be dismantled and erected elsewhere after the exhibition. The original design for the building was discarded as it required the use of 15 million bricks and it would have taken over a year simply to manufacture enough bricks, let alone build the building.

The entire building was constructed using an 8 foot module. This was based upon the maximum size of glass that could be manufactured at the time, and resulted in bay sizes of 24, 48 and 72 feet. Each bay, which consisted of 4 columns, 4 capital pieces and 4 trusses, could be erected in 20 minutes.

The building was dismantled and reerected on Sydenham Hill in a varied form, and stood there until the 1920's when it was destroyed by fire.

Paris: World Exhibition 1889:

Galleries des Machines. Charles Dutert architect and V. Contamin engineer. 1887-9. Destroyed in 1910. Building measured 115 by 420 meters, supported by three hinged arches. Two mobile trolleys installed to facilitate movement along the length of the building.

Gustave Eiffel (1832-1923): Eiffel Tower. Paris 1884-9: 1000 foot high parabolic vault. Sits at the termination of the axis on the Champ de Mars. Made of 15,000 prefabricated steel parts. Four inclined elevator systems serve the 200 foot level with two more continuing the relay to the 370 foot level. Another shuttle carried the visitors to the apex (served 2,350 visitors an hour). The guide rails for the elevators were used for the climbing cranes which were used to erect the building.

Horizontal forces diagram. "The first principle of architectural aesthetics prescribes that the essential lines of a building should be perfectly suited to its purpose. And what laws have I had to take into acount with the Tower? Resistance to wind. Well, I believe that the curves of the four outer ribs, as calculation has determined them .... will give a great impression of strength and beauty, because they will convey to the sight the boldness of the whole construction, in the same way that the numerous empty spaces contained within the elements themselves zill firmly stress the constant concern not to offer to the violence of high winds, surfaces dangerous to the stability of the building."

1900 World Exhibition: Paris

GRAND PALAIS: Built for the 1900 World Exhibition. The Petit Palais and the Grand Palais were built for the 1900 World Exhibition. The palaces' stone exterior, and steel and skylight architecture and varied exterior have always had critics as well as admirers but the constructions have gradually come to be admitted to the Paris environment.

THE CONSTRUCTION OF RAILWAY STATIONS:

In France on June 11, 1842 the Railway Code was established placing the responsibilities for the creation of a railway system in France. French railways were behind the British due to the high cost of iron and strict government control. Marc Seguin of France visited Robert Stephenson of England to get information. The British invested in the French railway lines. Passenger buildings had to be designed, for which there was no precedent architecturally. Often times no design relation between the front end buildings and the sheds to cover the trains and platforms.

Paris, Gare du Nord II. Replaced the original which had become too small. The first station was built in 1846, the second built from 1863-66, designed by Jacques Ignace Hittorf (whose first practical experience was under Belanger in the construction of the Halle de Ble). The facade is 180 meters wide, the shed is 200 meters long, 70 meters wide and 30 meters high. The eight tracks and four platforms of the shed are coveredd by a single continuously sloping gable roof.

England, Brighton. Original designed by David Mocatta in 1840-41. Present train shed designed by H.E. Wallis in 1883 and erected on arched ribs over the original shed.

England, York. Thomas Prosser 1857 - William Peachey 1877.

Scotland, Glasgow, Central Station. R. Rowand Anderson, 1879 completion. Later expanded to accomodate 13 platforms.

Chartres, Market Building. Developed a new variety of the old form during the 19th century. Inspired by the railway archiecture. Were constructed of iron.

Galleria. Napoli.

THE ADVENT OF MODERN MULTI STOREY STEEL FRAMING:

Auditorium Building. Chicago, Illinois. 1887-89. Adler and Sullivan. Longitudinal section. The interior framework of the Auditorium embraced every structural technique in iron available at the time.

Daniel Burnham and John Wellborn Root. The Monadnock Building. 1889-91. 16 stories on exterior walls of brick 6 feet thick at the base. By using girders projecting outward from their supports on the masonry piers, the architects were able to open the wwall into bow windows with such generous areas of glass as to belie the masonry construction. The interior floor and roof loads are carried on a braced iron frame distinguished by a
kind of bracing known as portal framing.

Le Baron Jenney (1832-1907). Home Insurance Building, 1885. Embodied most of the features of the skyscraper. First extensive application of the internal skeleton and the curtain wall to a high office building. Jenney's design criteria were: maximum durability, fire resistance, economy of construction, admission of natural light, open interior space for freedom of arrangement of the internal elements. Most advanced features of the framing system were the method os supporting each bay of the wall on a shelf angle fixed to the spandrel girder; the introduction of steel into the building frame. The frame included cast iron cylindrical columns, built up box columns of wrought iron, spandrel girders and floor beams of wrought iron up to the sixth floor, and Bessemer steel beams and girders above to the 10th storey. The connections of the frame were bolted as opposed to riveted, which was more common then.

Le Baron Jenney. Fair Store. Chicago. 1890-1. Detail of fireproof steel frame construction. Had all the structural features of the modern fireproof high rise building. Box columns, girders and beams of I sections, tile arches, portal bracing, riveted joints, fireproof tile cladding and concrete subflooring.

Daniel Burnham. Reliance Building. Chicago. 1894-5: the structural culmination of the Chicago school. The steel frame of this slender tower of glass is carefully braced in two ways: 24 inch deep spandrel girders provide the usual portal bracing, and two storey columns erected with staggered joints increase the rigidity of the vertical members. This was all that was possible until the advent of welding and rigid framing shortly after WWI. Cross section of window bay.

Chicago Tribune Competition:

The skyscraper had emerged in the 1870's in New York and Chicago as a response to the storage, merchandixing and managerial needs of railway and steampower trade.
Exploitation of land prices as well as functional necessity had forced the building upwards; steel wire, the elevator, and the steel frame had allowed this to occur. The typical structural anatomy combined a grid plan, partitioned spaces, and open facades, and this could lead to various possible vocabularies. Here was the core of an american dilemma: should the creature be left alone as function and finance suggested, a scarcely articulated object of engineering? or should the native invention be clothed in cultural dress imported from elsewhere and given the veneer of civilization?

Raymond Hood and John Mead Howells. Winning entry for the competition, 1922. Neo Gothic Style.

Eliel Saarinen's entry.

Giotto Campanile imagery.

Bruno Taut's entry.

Adolph Loos' entry.

Walter Gropius' entry.

Modern Skyscrapers:

Mies van der Rohe. Friedrichstrasse Skyscraper Competition of 1920.

Mies van der Rohe. Seagram Building, New York. 1954-58: With Philip Johnson.

John Hancock Building. Chicago.

Kohn, Pederson and Fox. 333 East Wacker Drive.

STEEL DEVELOPMENT IN MEDIUM TO SMALL SCALE BUILDINGS:

Industrial Buildings:

Peter Behrens (1868-1940) Karl Bernhard. AEG Turbine Factory. Hittenstrasse, Berlin. Germany. 1908: built various industrial buildings with the attitude of artist decorator, whose intention was to accommodate the functional elements with dignity and
Walter Gropius (1883-1969) and Adolph Meyer. Fagus Werk. Alfeld-der-Laine, Germany. 1911: Worked for Peter Behrens. Formulae acting as a means of chronological characterization, while the technical elements were organized in a taut, coherent way, though left almost completely bare, with all the freshness and tenseness that the situation allowed. Almost all the Fagus werks can be read in a purely technological light, since the stylistic demands are reduced to an extremely slight outer covering.

Pier Luigi Nervi (B. 1891):

Pier Luigi Nervi. Palace of Labour. Turin. 1960-1: Plan. Covered area of 270,000 square feet giving an exhibition space of 485,000 square feet. Comprised of 16 cast concrete columns with steel mushroom heads. Steel used instead of the original proposal of concrete due to speed.

IKOY. Northwest Recreation Centre. Regina, Saskatchewan. 1983

IKOY. Red River Community College. Winnipeg, Manitoba. Automotive Diesel School. 1983

Residential Buildings:

Pierre Chareau. Maison de Verre. 1928-32: Interior view of the salon.

Mies van der Rohe (1886-1969) Farnsworth House. Plano, Illinois, 1945-50: Son of a master mason. Worked with Behrens in 1908 and in 1911 with Berlage. The house is a steel skeleton of I beam supports welded to floor and roof frames. The supports rests on mzssive individual concrete footings. The frames provide perimeter channels which hold secondary I beams spanning the short direction. The spaces between these beams are filled in with precast concrete slabs, which produce the thin roof and floor planes. All pipes and other utility lines are compressed into one stack which connects the elevated house with the ground. Only building where Mies had the steel painted white, the favorite colour of modern architecture, which here contributes to the dematerialization of the structure by denying the steel a symbolic expression of its nature. Built for Dr. Edith Farnsworth.

THE DEVELOPMENT OF TENSION STRUCTURES: CABLES

The most extraordinary discovery in steel construction, was the discovery of a material whose tensile strengths exceeded its compressive strengths. Because of steel's ability to take tension, aspects of structural design changed. During the design of cast iron, stone, timber and plain concrete structures, the basic intent was to maximize the number of members subjected to compression (as they were all stronger in this regard). The inherent problem with this type of design, is that as members get longer, they become subject to buckling, sometimes long before their compressive strengths are reached. Because of this, members must be bulky and heavy to withstand buckling forces. When members are able to be designed to be in pure tension (stretching), even a slightly outdated grace (Wagner). Buckling never has the chance to occur -- hence the members may be very slender, and often cables and rods are used.

The first use of cables in structures occurred during the design of bridges. This is still a principle use, although, tensile members are used in buildings as well (although often less dominantly).

Normal hot rolled structural steel sections designed to take compression *or* tension. Cables and rods are designed for pure axial tension only.

- The Brooklyn Bridge. John A. Roebling and Washington A. Roebling. 1869-83.
- Piano and Rogers. Pompidou centre. Bracing detail
- Single and double layer cable supported roofs.
- Cable supported cantilever roofs.
- Single layer cable supported roof at Chicago O'Hare Airport.