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Castellated construction

«Ausgezahnte» Stahlbauten

Construção «ameiada»

Construction crènelée

H. SAUNDERS, A. I. Struct. E.

Director – United Steel Structural Co. Ltd.
Scunthorpe

The basic idea.

Methods of achieving economy in steel, with consequent reduction in the deadweight of a structure, while at the same time maintaining or increasing the strength of a given span, have been the objectives of the Consulting Engineer and Architect ever since steel framing as we now know it was accepted as an independent load carrying unit in building construction.

While castellated construction of a type had been used on the Continent to some extent, I feel it is correct to say that this method of construction had not been seriously investigated until 1937, when Geoffrey Murray Boyd was granted a provisional patent and ultimately a British Patent 498,281, and at the same time obtained Patent Cover in several countries outside Britain.

Largely, no doubt, due to the incidence of the War Period, the foreign cover lapsed but the British Rights have now been extended to 1960.

A series of tests were made to determine the correct shape and size of a castellation to produce a section which would normally be capable of taking a comparatively light load over a span of greater dimensions than average, with reasonable security against high bending stress, and also excessive deflection due to span. At the same time it was desirable that heavier loads could be carried over spans which would normally require a compounded section or the use of a much heavier member. It is, of course, appreciated that this problem of comparative sections is one which is particularly reflected by the much reduced range

of beams produced by British Rolling Mills in comparison with the greater availability of range in other countries.

The principle of castellation.

To meet the requirements of depth increase without weight increase, it is necessary to expand a standard rolled steel beam, channel or other suitable section, by a longitudinal cut in such a way, that when the two cut pieces are rejoined the resultant section has a depth which for practical considerations is maintained at one and a half times that of the original section.

This increase in depth (without increase in the weight) must obviously give an improvement in the geometrical properties of the section.

As will be seen from the tables (Plate No. 1) the major moment of inertia is increased by approximately 135 % while the corresponding section modulus is increased by approximately 56 %.

These increases are of considerable value in restricting deflection, while at the same time the resistance of the beam to bending is increased.

It must be emphasised that in the production of the castellation, more is involved than the mere cutting and welding of a beam to a shape which ultimately results in a series of apertures. The cutting must be calculated on a predetermined formula so that the greater capacity of the expanded section can be fully developed for resistance to bending and web buckling.

The line of the original cut in the basic section is so arranged that when the section is expanded and welded together along the neutral axis, the depth of the castellation opening is equal to the depth of the basic section. This arrangement, coupled with a suitable slope to the sides of the castellation opening, ensures full protection against the effects of longitudinal shear at the neutral axis, giving maximum shear resistance throughout the whole section and establishing as high a value as is possible in the capacity of the beam to resist web buckling stresses at the bearings, and at such points where concentrated loading may be applied to the beam.

Consequently it will be seen that the expanded sections have much improved properties to take loads over larger than normal spans without any increase in the weight of steel involved for the beam. In cases where short spans carrying very heavy loads are concerned, the castellated form of construction is not suitable as, in the majority of cases of this character, shear strength is one of the controls, and it will be obvious that the principle of castellation is not so readily applicable, owing to the web apertures. Nevertheless there has been no occasion, even including those cases when tests have been taken to destruction, where shear strength has proved the limiting factor.

Method of manufacture.

The two processes involved are burning and welding which are both within the capabilities of any Structural Fabricating Shop.

Castella Beam	Minimum Equivalent Joist or Joist Compound Section	Saving		Castella Beam		Equivalent Section		Castella Beam	Minimum Equivalent Joist or Joist Compound Section	Saving		Castella Beam		Equivalent Section	
		Wt. in lbs./ft.	Per-centage	Moment of Inertia x-x	Section Modulus x-x	Moment of Inertia x-x	Section Modulus x-x			Wt. in lbs./ft.	Per-centage	Moment of Inertia x-x	Section Modulus x-x	Moment of Inertia x-x	Section Modulus x-x
36 x 7½ x 95 lbs.	24 x 7½ joist with 1-12 x ½ plate on each flange-weight 160 lbs.	65	41	5918	329	4832	379	21 x 6 x 57 lbs.	20 x 6½ x 65 lbs. R.S.J.	8	12	1253	119	1226	122
								21 x 6 x 46 lbs.	20 x 6½ x 65 lbs. R.S.J.	19	29	1028	98	1226	122
33 x 7 x 75 lbs.	24 x 7½ joist with 1-12 x ½ plate on each flange-weight 140 lbs.	65	47	3911	237	3950	316	21 x 5½ x 40 lbs.	18 x 6 x 55 lbs. R.S.J.	15	27	883	84	842	94
								19½ x 5 x 35 lbs.	16 x 6 x 50 lbs. R.S.J.	15	30	662	68	618	77
30 x 7½ x 89 lbs.	22 x 7 joist with 1-12 x ⅝ plate on each flange-weight 130 lbs.	41	32	3910	261	3279	282	18 x 8 x 65 lbs.	22 x 7 x 75 lbs. R.S.J.	10	13	1163	129	1677	152
								18 x 6 x 54 lbs.	20 x 6½ x 65 lbs. R.S.J.	11	17	893	99	1226	122
30 x 6½ x 65 lbs.	22 x 7 joist with 1-12 x ½ plate on each flange-weight 120 lbs.	55	46	2863	191	2905	253	18 x 6 x 44 lbs.	18 x 6 x 55 lbs. R.S.J.	11	20	767	85	842	94
								18 x 5 x 32 lbs.	15 x 6 x 45 lbs. R.S.J.	13	29	516	57	492	66
27 x 8 x 80 lbs.	22 x 7 joist with 1-12 x ⅝ plate on each flange-weight 110 lbs.	30	27	3035	225	2531	223	15 x 6 x 40 lbs.	15 x 6 x 45 lbs. R.S.J.	5	11	485	65	492	66
								15 x 5 x 30 lbs.	15 x 5 x 42 lbs. R.S.J.	12	29	345	46	428	57
27 x 7 x 75 lbs.	24 x 7½ x 95 lbs. R.S.J.	20	21	2699	200	2533	211	15 x 4½ x 25 lbs.	10 x 6 x 40 lbs. R.S.J.	15	38	284	38	205	41
27 x 6 x 55 lbs.	24 x 7½ x 95 lbs. R.S.J.	40	42	1959	145	2533	211	13½ x 4 x 21 lbs.	10 x 5 x 30 lbs. R.S.J.	9	30	188	28	146	29
24 x 8 x 75 lbs.	24 x 7½ x 95 lbs. R.S.J.	20	21	2301	192	2533	211	12 x 6 x 35 lbs.	15 x 5 x 42 lbs. R.S.J.	7	17	266	44	428	57
24 x 6 x 62 lbs.	22 x 7 x 75 lbs. R.S.J.	13	17	1700	142	1677	152	12 x 4 x 18 lbs.	10 x 4½ x 25 lbs. R.S.J.	7	28	129	21.6	122	24.5
24 x 6 x 50 lbs.	22 x 7 x 75 lbs. R.S.J.	25	33	1442	120	1677	152	10½ x 4 x 16 lbs.	9 x 4 x 21 lbs. R.S.J.	5	24	93	17.7	81	18
22½ x 6 x 59 lbs.	22 x 7 x 75 lbs. R.S.J.	16	21	1477	131	1677	152	9 x 3 x 12 lbs.	7 x 4 x 16 lbs. R.S.J.	4	25	50	11.0	40	11.3
22½ x 6 x 45 lbs.	18 x 7 x 75 lbs. R.S.J.	30	40	1143	102	1151	128	7½ x 3 x 11 lbs.	7 x 4 x 16 lbs. R.S.J.	5	31	32	8.4	40	11.3
22½ x 5 x 42 lbs.	18 x 6 x 55 lbs. R.S.J.	13	24	1000	89	842	94	7½ x 1½ x 6.5 lbs.	5 x 3 x 11 lbs. R.S.J.	4.5	41	15	4.3	14	5.5
21 x 8 x 70 lbs.	20 x 7½ x 69 lbs. R.J.S.	19	21	1665	159	1673	167								

Mechanical longitudinal profile burning machines are used for the cutting process adjusted by means of steel templates, a separate template being necessary for each depth of section used, and in its preparation appropriate adjustments in profile must be made, so that the resultant cut in the beam is to the correct shape and size. Cutting is continuous with the exception of spaced intervals which must be left uncut (temporarily) in order to avoid undue distortion.

The two resultant pieces are then moved along one castellation or turned end-for-end and assembled by means of tack welding, and then fully welded by the deep penetration electrode technique thus obviating any edge preparation. It is essential to control burning and welding throughout all stages to avoid distortion and the consequent additional operation of straightening. To date no practical alternative method of preparing the two sections has been found to substitute for the gas burning process. The welding is done by manual operation. Alternatives, which would, however, involve a large amount of capital cost, are resistance welding and forge welding.

British Patent 713,794 has, however, been granted to cover a mechanical forge welding process which is also covered by Patents in the majority of countries outside Great Britain.

Variations of the castellated system.

The castellated form of construction can, of course, be applied not only to standard rolled beam sections, but with equal facility to other sections, and in fact to a combination of two varying sections whether of the same type or not. These variations are detailed on Plate No. 2 which also illustrates two types of cruciform sections, the fabrication of which is also simplified by the use of the castellated construction system.

By a variation in procedure, tapered beams can also be formed not only at a lower cost, but with a still further saving in material. This is accomplished quite simply by directing the line of cutting along the web at a pre-determined angle to the flanges, thus by turning one portion end-for-end the tapered section is formed.

It will be realised that the system can provide for an infinite variety of sections in castellated form.

Economies of the system.

Plate No. 1 is a self-explanatory table which shows in detail the savings in weight of steel by the incorporation of castellated beams of equivalent or greater strength to the minimum equivalent rolled steel joist or joist compound section. These comparisons are, of course, made with British Standard rolled sections.

Plate No. 3 shows the typical load-span relationship of a $36'' \times 7 \frac{1}{2}'' \times 95$ lbs. castellated beam as against a British Standard rolled joist $24'' \times 7 \frac{1}{2}'' \times 95$ lbs. and is for convenience shown in graphical form.

The portion of the curve A - B indicates the permissible load governed by the extreme fibre stress of 10 tons per sq. ins.

At point B deflection begins to control the permissible uniformly distributed load as in no case is the load allowed to exceed a value at which the deflection would be more than $1/325$ span.

The maximum uniformly distributed load on a castellated beam with its compression flange laterally supported, is controlled by the buckling

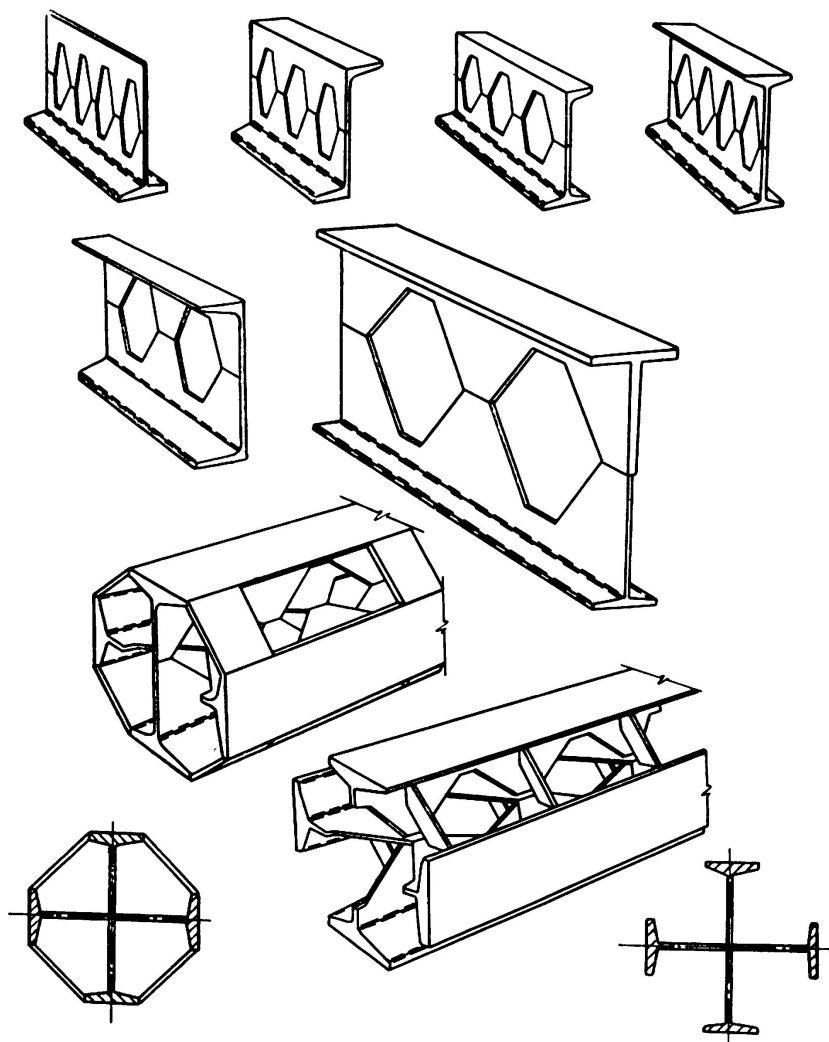


PLATE N° 2. Typical applications of castellated construction

value of the web. The length of web on the neutral axis of the section between the end of the beam and the first castellation is standard for each section. The safe web buckling value of this portion of web thus controls the maximum permissible end reaction, and hence the allowable load on the beam. This value is shown on the graph by point C, and is the maximum safe load with end castellation left open. The area of web under buckling and hence the maximum permissible load may be increased by filling in the end castellation. This increased value is indicated by point A on the graph.

The values for web buckling are calculated on a minimum bearing length of $1''$ for all castellated beams over $13\frac{1}{2}'' \times 4'' \times 21$ lbs. and on a length of $\frac{1}{2}''$ for all smaller sections. In all cases where the safe

web bearing load is less than the safe web buckling load point A is established by the former.

The summary of all factors demonstrate that the main applications are in such cases where comparatively light loads have to be taken by means of beams of large spans, or greater length, than would normally be encountered.

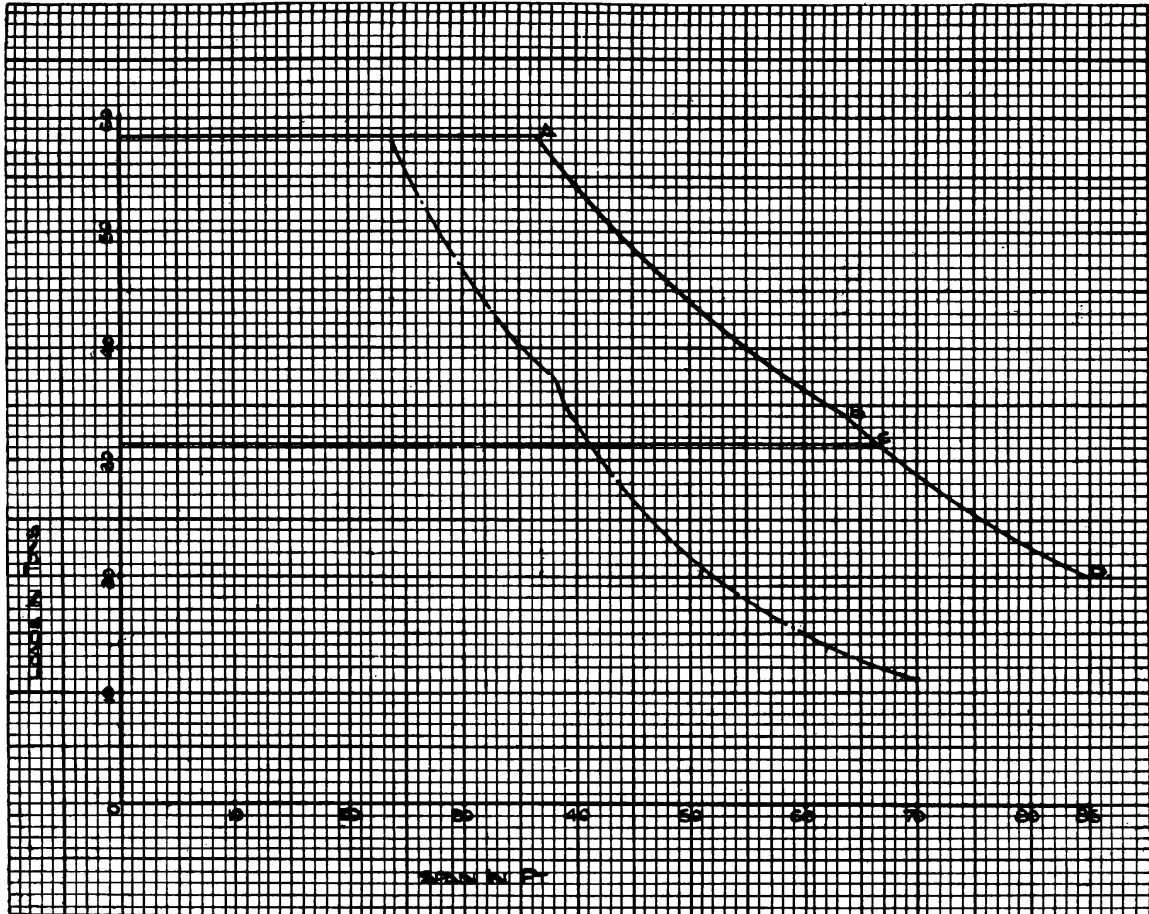


PLATE N° 3. Typical load span relationship between 24" x 7 1/2" x 95^{lbs} rolled joist (chain dot) and same joist castellated to 36" x 6 1/2" x 95^{lbs} (full lines)

Broadly speaking, and despite the increased fabrication costs which are involved, it can be stated as a result of experience, that the average saving in weight varies between 11 % and 47 %, and as a rough guide it has been found that the saving in money is approximately half that percentage, i. e. say from 6 % to 24 %.

A specific comparison was made in the case of a typical office type building, consisting of three storeys with flat roof, the overall dimensions of the building being 195 feet long, 50 feet wide centres of stanchions with a storey height of 12 feet, and a total height of 36 feet. The clear span of the floor beams was taken at 50 feet, and the centres of the columns in the length of the building 13 bays at 15 feet.

Only the main floor and roof beams were assumed as being made

up in castellated construction. The columns, wall beams and tie beams were allowed for in normal rolled sections.

The following is an analysis of the comparison of the steel weights: — saving in weight of castellated design on the rolled section design — 32.5 %.

Design with Rolled Sections		Design with Castellated sections
200 tons 15.32 lbs.	Total weight of steelwork... ..	135 tons
	Weight per sq. ft. of floor area	10.34 lbs.
	Weight per cu. ft. of building capacity (gross cube of building dimensions on centres)	0.86
1.28		

In the rolled section design, allowance was made for flange plate curtailment on the 50'0" span, roof and floor beams. Both the roof and floor beams are compounded in the rolled section design, but there are no compound sections whatever in the castellated design.

Research investigation.

During the course of the development of castellated beams, it became increasingly evident that practical tests should be made on the sections in regard to load capacity, such tests to have particular reference to the effects of web buckling stresses. It is obviously of primary importance to ascertain what stresses and strains arise in a given section from such practical tests as a check on the calculated values, particularly as in the case of castellated beams we are dealing with a section involving certain complexity of stress conditions.

One of the most direct methods of approach to the question of the strains set up in such a section, is by means of the use of electric resistance strain gauges. This method was decided upon after consultation with the United Steel Companies' Research and Development Department, and it was agreed at this stage to carry the tests to destruction.

In regard to web buckling, it will be clear that it must be assumed that some reduction in bearing capacity of the web should be allowed for, relative to a normal rolled steel beam, and this in point of fact is done, as clearly the amount of web available for resistance of buckling stresses over the bearing or at any point where concentrated load may be applied is considerably reduced. Nevertheless a number of tests, all of which have been carried to destruction, have shown that the ability of castellated beams to resist web buckling stresses is higher than might be at first apparent.

The experimental work was conducted primarily to check the theoretical assumptions in this regard, particularly as the primary calculations made in reference to these sections involved a great deal more than a direct application of the ordinary beam theory. A comprehensive set of resistance strain gauges was attached to the test beams so that a final analysis of the results would give a full picture of the behaviour of the sections under load. It is notoriously difficult to simulate the conditions of uniformly distributed load on a beam for test purposes, and in

consequence it was decided to use two point loads placed at the quarter points of the span so that the end reaction and the maximum bending moment would be equal to those given by a uniformly distributed load over the whole of the span equal in magnitude to the sum of the point loads.

The top flange of each beam was restrained against lateral failure by a «point contact» lateral support at mid-span so that the test conditions would comply with the requirements of B. S. S. 449/1948 in regard to lateral buckling of the compression flange.

Plate 4 shows the end section of one of the beams after failure had occurred and indicates a typical web buckling failure — the web having

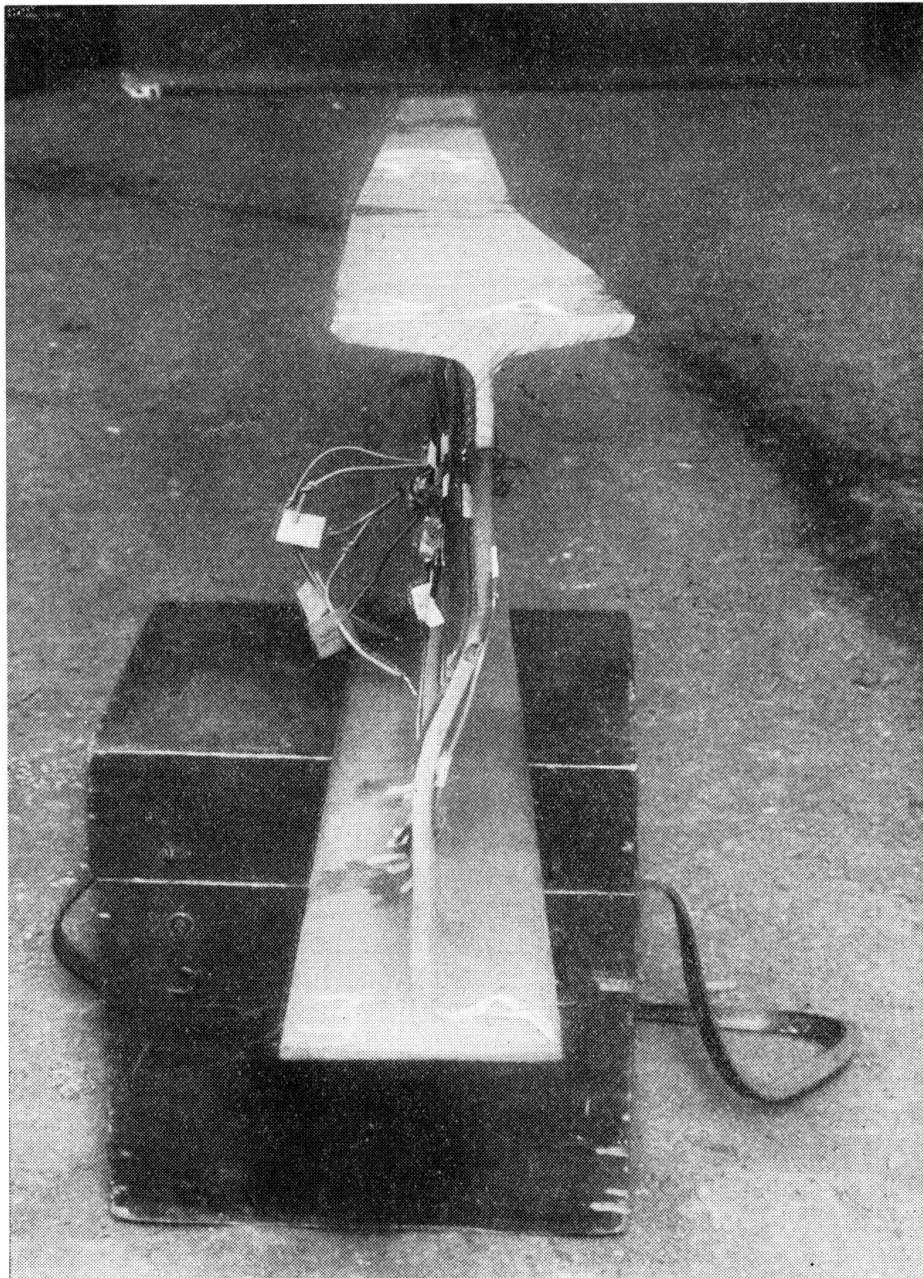


PLATE N° 4. Web buckling test confirming assumed type of failure under overload

double curvature as would be expected. All the beams tested under these conditions eventually failed by web buckling, this being the object of the tests.

It may be stated that during the tests in no case was any failure by web buckling observed, until the loads applied to the beams had reached the region of some three and a half times the value which would normally produce a bending stress of 10 tons per sq. in. in the flanges, under conditions where lateral support is provided to the compression flange during loading.

At this stage it is considered that the action at the abutments is in some part that of a homogeneous section, for the other part that of a rigid welded lattice girder. Work is still proceeding on this particular matter as it is felt that theoretical analysis of the beams is not likely to give an accurate reproduction of the true state of stress conditions.

The standard of welding is maintained by the periodic use of Gamma-radiography, particularly to ensure that the welder himself can have visible evidence as to the quality of his work. This opportunity is very much appreciated by the operatives, and there is no doubt that it helps to maintain the highest possible standard.

Two types of isotopes are normally used.

For material up to three quarters of an inch in thickness, a 4000 milicuries Iridium 192 is satisfactory. The pellet is changed every 20 weeks.

A 1000 milicuries cobalt 60 is satisfactory for material over 1 inch in thickness. This pellet only needs changing every 5 to 7 years.

Practical applications.

Although the use of castellated construction is not restricted to steel framed buildings, available space precludes the illustration of more than three specific types.

Plate No. 5 shows the incorporation of castellated beams in a saw tooth pattern roof in a factory for the production of typewriters. The building is 310' long and the castellation outlines have a considerable effect on the general appearance of the structure, as well as being a light, stiff section for the long members.

Plate No. 6 shows the floor beams in a four storey Technical College in the North of England where the pre-cast floor slabs run on shelf angles which leave at least half the castellation open underneath to permit the passage of service pipes and cables. As the ceiling is suspended at the bottom flange level the finished building is clean in appearance, services are concealed, and floor thicknesses kept to a minimum.

Castellated construction is equally applicable to portal frame or rigid frame industrial buildings, of which that shown in plate No. 7 is typical.

This method of construction has been used with considerable success in light single lane road bridges, a typical example of which is for a roadway 8'6" wide consisting of seven spans of 50' the members being 24"×7 1/2" Joists castellated to 36"×7 1/2".

The system has also been used for light crane bridge girders and for light gantry girders.

Conclusions.

It must be accepted that an approach to the theoretical maximum economy in the use of steel is hindered by the range of hot rolled sections, and the possibility of alternatives such as cold formed sections is limited by practical applications, particularly for the heavier type of structure.

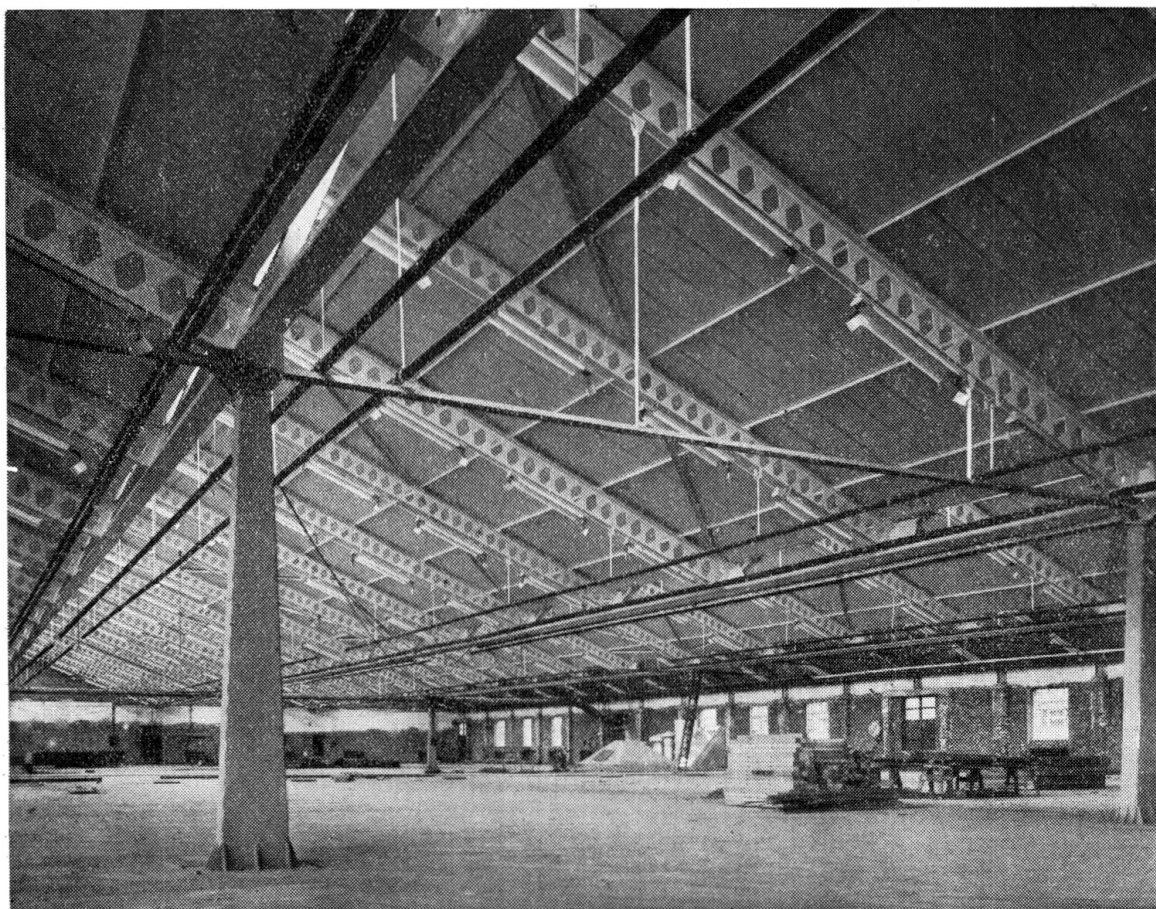


PLATE N° 5

The facility to «stretch» a standard section so as to be equivalent to several higher sections in the standard range means that on a structural contract which would normally require a large number of different sections, the whole requirements can be met with a smaller number of sections, ordered from the mills and expanded to the required depth and strength.

In view of the present heavy demand on the steel industry, this enables Structural Engineers to simplify their orders on the Rolling Mills and so fit them in with rolling programmes resulting in earlier

deliveries, and at the same time achieving economies in weight and cost of the finished structure with further resultant savings in foundation costs.

Great efforts are being made throughout the world at the present time to produce structures in steel which possess aesthetic appeal coupled with economy of material and workmanship. Consequently investigation in detail of various up to date constructional methods has been made. Of such methods it may be said that castellated construction is in the forefront.

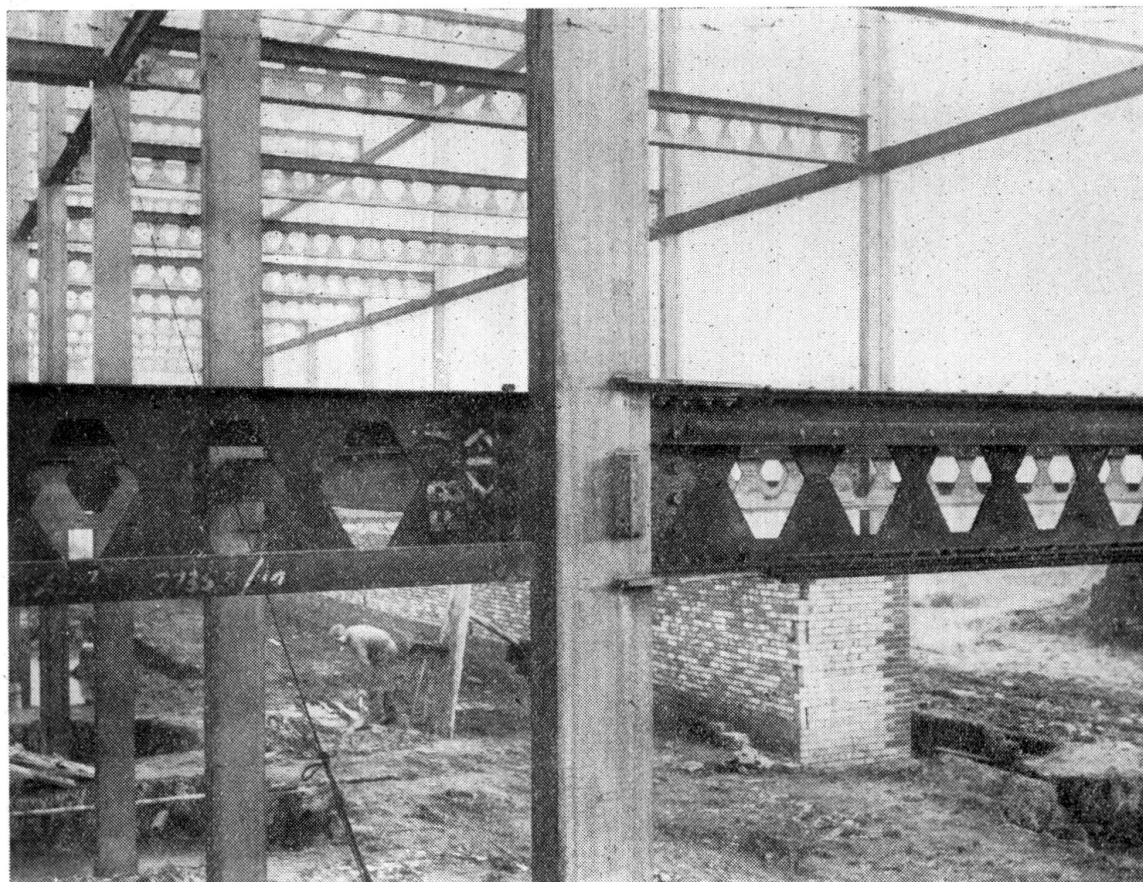


PLATE N° 6

The system possesses many desirable features, being economic in steel, and adaptable in application. The method is well suited for repetition work or for the more specialised treatment required in the individual design of «one off» structures, particularly where callisthenic features are of importance, as the basis of the system is conducive to a light and delicate appearance of the completed frame, and the various components possess a pattern easily incorporated into an aesthetically pleasing whole.

I have endeavoured to show that all these points can be met by the adoption of the castellated method of construction.



PLATE N° 7

Acknowledgements.

I am indebted to the Directors of United Steel Companies Limited for permission to incorporate information formulated in connection with their «Castella Beams», and to reproduce their copy right photographs.

Also to members of the technical staff of United Steel Structural Company Limited for their collaboration and assistance in the preparation of much of the data which has been included in this paper.

S U M M A R Y

The principle of castellated construction is that of cutting the web of a steel girder in a series of serrations or teeth, and subsequently welding the pieces together after they have been rearranged so that the depth of the completed member is 50 % greater than that of the original member, with appropriate increases in the major moment of inertia and the section modulus.

The paper incorporates not only the method of manufacture of standard beams, but indicates variations of the principle, whereby combinations of unlike members can be treated in the same way.

Information is given which shows the saving in weight of steel to produce members of equivalent or even greater strength than the original beam, and gives illustrations of practical applications of the castellated system in steel framed buildings.

ZUSAMMENFASSUNG

Das Wesen der ausgezahnnten Bauweise besteht in der Trennung eines Stahlträgers im Steg längs einer Zacken- oder Zahnlinie und im nachfolgenden Zusammenschweissen der gegeneinander verschobenen Teile. Die Höhe des zusammengefügteten Trägers ist damit 50 % grösser als jene des ursprünglichen und entsprechend erhöht sich auch das Hauptträgheitsmoment und das Widerstandsmoment.

Der Beitrag enthält nicht nur die Herstellungsmethode der Standardträger, sondern auch Abweichungen vom allgemeinen Vorgang, wobei Zusammenstellungen ungleicher Teile auf die gleiche Weise behandelt werden können.

Gegenüberstellungen zeigen die Stahlgewichtersparnis bei der Herstellung von Trägern gleicher oder sogar grösserer Tragfähigkeit, und in praktischen Beispielen aus dem Stahlhochbau ist die Anwendung dieser Bauweise ersichtlich.

RESUMO

Em princípio, o processo de construção «ameiada» consiste em recortar a alma de um perfilado metálico em forma de dentes, em deslocar seguidamente, uma em relação à outra, as duas peças assim obtidas e soldá-las, ficando finalmente a viga com uma altura de 50 % superior à do perfilado original o que aumenta consideravelmente os momentos de inércia e resistência da secção.

O autor, além de descrever o método de obtenção de vigas correntes, indica ainda variantes permitindo combinar perfilados diferentes pelo mesmo processo.

Dão-se também indicações acerca da economia de peso realizada em vigas de resistência equivalente ou superior à do perfilado original e descrevem-se aplicações práticas deste sistema em estruturas metálicas.

RÉSUMÉ

Le principe de la construction «crénelée» consiste à découper l'âme d'un profilé métallique en forme de créneaux, à déplacer ensuite l'une par rapport à l'autre les deux pièces ainsi obtenues et à les souder enfin, de façon à obtenir une poutre 50 % plus haute que le profilé original, ce qui permet d'augmenter considérablement les moments d'inertie et de résistance de la section.

L'auteur décrit le mode d'obtention des poutres les plus courantes et indique des variantes permettant de combiner des profilés différents par le même procédé.

Il donne également des renseignements sur l'économie de poids réalisée sur des poutres de résistance égale ou supérieure à celle du profilé original et décrit des applications pratiques de ce système dans des charpentes métalliques.