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Economics of framed structures†

by

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Mr Donovan H. Lee (Consulting Engineer) questioned the accuracy of the comparative costs given in Fig. 15. He had found shell roofs more competitive for large spans than shown there, but for spans of 100 ft or more, prestressed concrete beams in conjunction with a light roof construction should be cheaper, where suitable, and there were important recent examples of them.

135. Mr Lee felt the comparative weights of steel needed for roof constructions of cold-formed sections, and of tubular steel, could be misleading unless it was borne in mind that increased cost of fabrication and, where applicable, of the material itself, could, and usually did, make the total cost equal or exceed that of the heavier construction using ordinary rolled sections.

136. The present relative costs of several types of beams of 24-ft span was shown by Table 1. The small effect of increases of 10% in cost of formwork, concrete, or structural steel could be seen. The effect on the Author's comparisons of varying relative costs, for example, overseas, could be estimated in this way.

TABLE 1.—RELATIVE COSTS OF STEEL, CONCRETE, AND P.R.C.

Case I: Beams with concrete slab
(all costs of slab are omitted)

	Cased steel	Cased steel composite design	Reinforced concrete	P.R.C. composite design

Relative weight (ignoring slab) . . .	100	132	125	125
Relative cost	100	93	56	65
" " (steel increased 10%) . . .	100	92	54	63
" " (concrete " 10%) . . .	100	93	56	65
" " (formwork " 10%) . . .	100	93.5	57	65.5

Case II: No slab

	Steel R.S.J.	R.C. beam	P.R.C. rectangu- lar	P.R.C. I-section

Weight	100	810	550	357
Cost	100	95	96.5	103
" (steel increased 10%) . . .	100	90	90	98.5
" (concrete " 10%) . . .	100	97	98	104
" (formwork " 10%) . . .	100	99	97	108.5

† Proc. Instn civ. Engrs, vol. 12, p. 237 (March 1959).

137. He did not criticize the Author's general conclusions about the relative cost of frames, and the Author was in a good position to be fairly sure of his facts, but with all forms of framed structure it was necessary to take account of the secondary effects, as the Author had said when introducing the Paper.

138. Structural steel usually needed less depth of beams, as could be seen from Fig. 39, so where the clear height under them determined the storey height there was extra height of external walls, internal finishes, and vertical services to credit in its favour. Of course, shallow concrete beams with more reinforcement, and also the beamless floors referred to by the Author, enabled similar saving in walls and vertical services to be made.

FIG. 39

139. This seldom concerned multi-storey domestic buildings, because doorways formed the limit, but in those cases where the clear height below beams determined the storey height, it nearly always paid to spend more on shallower beams. For example, in a building 40 ft wide by 200 ft long there would be 0.06 lin. ft of wall per square foot of each floor, and per foot of depth of the deepest beams at each storey there would be 480 sq. ft of wall. Assuming the cost of the wall, the internal finish, and the vertical services to be 50s/sq. yd of wall, then for floor spans of 14 ft 3 in. it was worth 1s 2d/lin. ft extra cost of the beams to make them 3 in. shallower.

140. The dead weight of the structure affected its own cost, but notwithstanding the variation in relative weights given in Table 1 this was unimportant compared with the floor loading and its dead weight, which meant the span of the floors was the more important. Fig. 40 showed the cost of carrying weight in the case of steel-framed buildings. A similar graph could be made for reinforced concrete framing or a suitable relative cost factor used from the Author's examples.

141. Apart from enabling the total weight and cost of a framework to be estimated approximately once the spans and heights were decided, it was useful to find if it was economical to pay more for lighter external walls or partitions or lightweight concrete because of saving in the framework, or to find the saving due to lighter floor constructions, such as prestressed concrete, if the spans were large.

142. Fig. 40 gave the cost of the steel framed structure designed to current stresses with allowances for cleats, slab bases, etc., and also for some unavoidable excess metal in stanchions continuous through more than one storey.

143. The cost scales enabled particular cases to be dealt with, for example, if stanchions were priced differently from beams.

144. Curves for the beams were given for loadings per linear foot of 1 ton and 2 tons and the curves were based on the lightest weight of steel for the resisting moment, which explained why the curves based on broad-flange beams were not quite in line with those of the normal B.S. sections.

FIG. 40.—COST OF CARRYING WEIGHT BY STRUCTURAL STEELWORK

145. To use the graph to obtain the total cost of the framework it was necessary to find the weight carried on each floor and the average beam span so that the cost of the beams for each level could be totalled. The cost of the stanchions was taken for each floor and separately totalled per ton and multiplied by the total load carried.

146. The curves including the encasing enabled the whole cost of the framework, floors, and encasing to be obtained by adding to what was obtainable from the graph the separately computed cost of the floors.

147. The Paper did not appear to give many cases where prestressed concrete was cheapest. Prestressed concrete beams were usually definitely the cheapest where the shear was great and usually also where the span was large; certainly where both applied.

Mr G. P. Manning (Consulting Engineer) did not think that the Author had laid sufficient emphasis on the extent to which site conditions would influence the choice of a particular form of construction. There were at least four conditions which generally favoured the adoption of structural steelwork: (i) a very small site, particularly if the edges were confined; (ii) a very irregular site; (iii) a site where the natural cross-

sections were paralysed by the planning experts and it was necessary to set back on the floors; and (iv) where the engineer at the outset had a very shrewd idea that his clients did not really know what they wanted, and it was extremely likely that there would be drastic alterations to the framework both during erection and after completion.

149. On a crowded city site the working space was always very small and it was not unusual to find half-a-dozen other subcontractors all trying to work in it at the same time. Any type of construction which required a minimum working space and a minimum labour force on the site was of great advantage to everybody, but it was extremely difficult to assess the total saving which was made thereby.

150. The Author had not sufficiently emphasized the importance and relative value of the proper functioning of a building from the client's point of view. Mr Manning showed details of a warehouse which had been built 8 or 9 years before. The floor of the warehouse had been raised above the road level to give loading bays and the roof was carried by conventional trusses, as shown in the left-hand part of Fig. 41. Immediately after that warehouse had been completed the clients had installed a fork-lift truck to handle their merchandise and found that they could easily have stacked up to the ridge, but were prevented from doing so by the members of the trusses and the bottom chord bracing, and so when they wanted another warehouse it had been built with a lattice steel shed frame (right-hand part of Fig. 41). This had been 20% more expensive than the trusses, but the cost of the steelwork in this comparison was only about 15% of the total cost of the warehouse, so that the difference in cost of the lattice form of construction amounted to only about 3% of the total cost, and the effective storage height—the effective value of the building—had been increased by about 30%.

FIG. 41

151. Fig. 42 showed a form of flat roof construction which had been fairly recently developed. The top and bottom flanges were sheets of corrugated aluminium alloy, or possibly aluminium troughing, and the shear was taken by little lattice girders. Roof units of this type had been made and tested up to 90-ft span.

152. From Fig. 15 it appeared that 100% of the weight for the 130-ft span was 12 lb/sq. ft, and the percentage unit weight figure for the prestressed concrete barrel was 20, which would mean 2.4 lb/sq. ft, equivalent to an average thickness of the concrete of $\frac{1}{4}$ in.

Mr C. A. Wales (Assistant Chief Quantity Surveyor, Ministry of Works), said that as a quantity surveyor he was particularly interested in the cost aspect of the Paper.

154. He had been glad to find that the relative costs had been given in the form of percentages because any figures quoted were remembered for ever after and it was always recalled that the cost of something was £x/ft. It was not possible, however, to

study the merits or demerits of a form of construction without going into costs in some manner.

155. Maintenance costs, which had a very big effect on the ultimate value to the client, were not covered in the Paper. In dealing with relative costs in the form of percentages it was extremely difficult to make a statement which applied to more than one case; each case must be examined and treated on its merits. Examination of tenders over a number of years revealed that while the two lowest tenders for a particular job might differ by only 2%, the figures in those two tenders for the trade of concretor might differ by 25%. In reviewing these relative costs, therefore, he suggested that where there was a difference of say 5–10% between two cases in the Paper they should be regarded as about the same, with the possibility of the figures being reversed on particular jobs.

FIG. 42

156. Market interest was very important in relation to costs. Often when a new method was introduced quite competitive prices could be obtained, but once the method had become attractive the cost gradually increased.

157. The question of relative foundations did not appear to have been taken into account in the various schemes mentioned.

158. In Fig. 20, in which the percentage cost for the steel frame was shown as 90 and for reinforced concrete as 100, Mr Wales understood that the steel frame referred to was uncased.

159. Uniformity in size effected great savings in the cost of construction, particularly in reinforced concrete. So far as possible standard sizes should be used even for the cross-sections of beams and stanchions, because it was more economic and it helped in setting out and doing the job. The designer should not only aim at this but show on the drawings that it had been done, so that those who were interested would see at once that it was so and not have to ascertain it for themselves. In billing, the quantity surveyor could draw the attention of contractors to it, so that they could take advantage of it. Was it not possible in reinforced concrete to have standard sections for the concrete in the same way that there were standard sections for structural steel, so that specialists in formwork could design it to suit the standard sizes? The cost of the formwork on average was approximately 40% of the cost of the beam, the cost of the concrete being about 30%, and the cost of the reinforcement also about 30%.

Mr C. S. Gray (Technical Adviser, British Constructional Steelwork Association) said that the Author's weight figures for structural steelwork were most economic and were if anything fractionally under the weights which Mr Gray would use for estimating purposes, but in the commercial field it was better to be a little over than under; there were always difficulties in putting the price up.

161. In the matter of cost comparisons the Paper was excellent as a record of past history, but it could not be of much use for the assessment of work in the future. It might be that when prices settled down the same relative proportions would obtain, but he thought not, because much had happened since the most recent prices in the Paper had been obtained, which must have been early in 1958. Today, for the first time for 20 years, the rolling mills were looking for orders, and that had had a tremendous impact on the prices for structural steelwork, and for the first time in 20 years it was

possible to make a job in the order in which the contract required it and not according to the material which was in stock.

162. Market interest was a very real matter to those in the construction field. There had been a marked diminution in building and civil engineering works generally, and more attention was being paid to weights and costs, but it seemed that there had been a bigger percentage fall in structural steelwork prices than in the prices of some of the other materials.

163. The main factor which was going to alter the cost ratio in the immediate future, however, was, he thought, the imminent issue of B.S. 449, which was going to increase stresses all round by approximately 5%. Concrete-encased columns would be permitted to carry loads up to 100% in excess of naked steel and laterally unsupported beams would no longer be of real consequence. Those factors alone would result in a reduction in weight and in cost of possibly 15% in favourable circumstances. It was not possible to judge the future by the past for Government buildings.

164. Still less could past costs be used as a yardstick for future commercial multi-storey work. Mr Gray was not critical of the designs put out by the Ministry, but two facts stood out. First, in designs for multi-storey buildings the stanchions weighed more as a percentage of the whole weight than they did in a building designed by a consultant or commercial firm to the ordinary requirements of B.S. 449. Secondly, the weight of details would be found to be greater in the Ministry designs than in commercial designs, and both these, unfortunately, were the more expensive elements of the frame. It could always be expected that a commercial job would command a lower rate than a Ministry of Works steelworks job. That lent force to the statement that it was not possible to judge the future of commercial office buildings in Britain by reference to the Author's past experience.

165. For the aluminium roof framing shown in Fig. 14, the aluminium cost was shown to be 135% of that of the steel. The relative costs of steel and aluminium for a similar building were given as 100 and 245 in a recent article.* He was sure that there must be some explanation for this.

166. Mr Gray disagreed with the statement in § 16 that "The relative cost of simple and complex fabrication is of the order of 4:5." Fabrication costs for structural steelwork, including direct and indirect on-costs but not profit, could vary by 5 or even 10 times, according to the nature of the workmanship and the amount of the material to which it was applied. In his view the ratio of 4:5 should be more like 1:2½. It was quite easy to get material and fabrication costs up to £150/ton, particularly when the job was "cluttered up" with welding.

167. There were a few other figures on which he disagreed mildly. A 10-ft spacing for 50-ft-span trusses was not the most economic. Trusses were the only members in which minimum size sections were apt to occur, i.e. sections with some size determined by other than purely stress considerations. Forty years ago nothing less than 2 in. × 2 in. × ¼ in. had been used, and that it had now come down to 2 in. × 1½ in. × ⅜ in. Whatever section was chosen, the closer the trusses were put together the more effect, and he thought that a wider spacing would give a slightly better job.

168. In § 56 it was stated that "The area covered by the frame with a rectangular grid is 50% greater than the square module for a framework of comparable weight and cost." The unit weights were approximately the same, so that he thought there must be an error there.

169. He emphasized that what had happened in the past was not necessarily a guide to the future.

Mr A. V. Hooker (Partner, W. S. Atkins & Partners, Consulting Engineers) commented on the type of large-span frame shown in Fig. 17.

171. While the structural frame was a major item in the cost of any building, its design could greatly influence the cost of other items, and the cheapest frame did not

* Struct. Engr, vol. 37, (Apr. 1959), p. 105.

always mean the cheapest building. Flat or very-low-pitched roofs had the advantage in multi-bay buildings of obviating the need for valley gutters and internal drains, and of reducing the dead space and therefore the cost of space heating and painting. Flat roofs, in which the horizontal component of the roof load was negligible, permitted the use of lighter purlin sections. The size of the purlins was usually governed by the vertical or lateral deflexion rather than by the limiting stress, so that if the purlin centres could be increased from, say, 4 ft 6 in. to 9 ft by using a suitable type of roof cladding there would be an appreciable weight saving.

172. Coming to large-span buildings, it must be expected that for spans of 100 ft and more a lattice structure would be more economical than a solid-web-type frame. He had been surprised, however, to see that in Fig. 17, diagram 5 (the solid-web portal), the main frames had been spaced as close as 20-ft centres, which seemed to be rather too close for economy with a span of 200 ft. He quoted some comparable figures for two frames with which he had dealt recently. The first was for a transit shed, using a 5°-pitch roof on a two-pin-arch frame, with site-welded splices (Fig. 43). The relevant weights were given in the Table in Fig. 43 and compared favourably with the solid-web portal of Fig. 17. There were two advantages in using the mansard treatment at the knee: it reduced the bending moment and it gave a better arrangement for the glazing, and so better natural lighting.

WEIGHTS: LB/SQ. FT OF FLOOR COVERED

Portal frames only	3.7
R.S.J. purlins	4.7
Bracing, side and gable framing, and bolts	3.6
Total	12.0

FIG. 43.—FRAME FOR 102-FT-SPAN TRANSIT SHED

173. For larger spans, of about 200 ft, there was a case for using a true arch if arrangements could be made to take the end thrust economically. Fig. 44 showed a 200-ft-span market building, using welded steel H-section arches with 33-in.-deep web and 12-in.-wide flanges (Fig. 44). The thrusts were taken by horizontal reinforced concrete beams, which formed the roof over a number of shops, and by end ties, so that none of the thrusts had to be taken by the foundations. In this case the total weight was 12½ lb/sq. ft of floor covered.

Mr J. N. Lowe (Consulting Engineer, Managing Director of The Pre-Stressed Concrete Associates) said that he wished to confine his comments to multi-storey frames. The analysis of multi-storey frames which the Author had made seemed to show that given a reasonable column module, which was a primary factor in cost,

FIG. 44.—FRAME FOR 200-FT-SPAN MARKET BUILDING

variation in the slide rule design might affect the structural cost by about 10%. Since the structural cost was probably between 25% and 40% of the total cost of the building contract, that meant that it was a matter of about 1% to 4% of the total cost which could be affected by the structure alone. In other words, there was a limit to the amount of money which could be saved by the engineer alone operating his slide rule. He proposed therefore to consider this 1-4%.

175. It could be completely overshadowed by the method of billing, the method of tendering, and the method of contract procedure. That seemed to be one of the main ways in which engineers, in combination with architects and quantity surveyors, could start to save costs. Were they necessarily wedded to the ordinary tendering method? Did it necessarily save costs?

176. There was a considerable number of media and methods from which to choose when starting to design a scheme. The consulting engineer and architect together, when dealing with the building frame, ought, strictly speaking, to consider steel and concrete and perhaps timber and aluminium and some patent building frames and in the end the whole cost of design, which was part of the cost of a building, and the time taken in design which was again part of the cost of building, would go up. Was there not a case therefore for thinking of other ways of providing oneself with a contractor than the normal tendering method? If one chose the contractor at an early stage one would know the plant, labour, materials, and method available for construction and one could probably design with that knowledge. That would give an opportunity to save more money than this 1-4%.

177. This raised the old thorny question of the negotiated contract. Mr Lowe was not recommending the wholesale scrapping of tendering methods but was asking for deeper consideration to be given to methods of selecting a contractor earlier than was possible by the old method. He had in mind his own firm's experience of a competition on a rough project scheme with rough quantities with unit rates and with basic rates, so that a contractor could be selected on this competition and could be of assistance during the general design not only to the engineer but also to the architect and quantity surveyor.

178. There were many hidden costs in the normal contract procedure for tendering, such as innumerable estimating costs from unsuccessful tenderers and their unsuccessful sub-contractors which were worthy of examination for economy. In any case there was perhaps a growing number of contracts which were put out with so many provisional sums that the normal tendering method hardly gave the competition that it was designed to meet.

179. The engineer could help in methods of building, which was one of the ways of saving money that Mr Lowe thought offered more hope than the 1-4%. It was a question in a frame of cutting down the price per cubic foot of concrete. The engineer should consider easy detail, easy erecting order, compatible crane lifting, and so on. If the contractor were chosen at the start the engineer could work with him—not too closely and at times ignoring him but at least knowing how he wished to do the job, what he was going to do it with and designing for the cheapest method of erection in all the circumstances. For instance some contractors preferred precast work and some preferred to cast in situ. With a normal design put out to tender a precast design might place the contractors in the order 1, 2, 3 but an in-situ design for the same job might place the same contractors in the order 3, 1, 2 and the variation could be considerable. The usual tendering method from one design only would not reveal whether (1) with the precast design was cheaper or dearer design than (3) with the in-situ design. Should the engineer do two designs or should a different method of competition be adopted?

180. Mr Lowe further thought that the 1 to 4% was completely overshadowed by various site conditions—the shape of the site, the amount of underpinning, the foundations, and so on. It was overshadowed in the run of the contract by allowance for bad weather, by variation in materials and labour not to mention the ordinary variation in tender at the start.

181. He did not mind what the frame cost if overall economy was secured and it was the job of the engineer to combine with the architect to produce that overall economy and satisfy the building owner by giving him the building he wanted.

182. In considering overall economy Mr Lowe felt that a wider column module, which was necessarily structurally more expensive, might still be more sound financially to the building owner.

183. Also in considering overall economy having chosen the structural medium and perhaps the contractor, the engineer must assist the architect in layout. Mr Lowe's firm had recently, at a structural cost of about 10%/sq. ft extra, managed with the architect to save about 20% of the total floor area. There was obviously a saving there. Also by having a reasonable structure—by co-operating at an early stage with the engineer responsible for heating and ventilating, and so on—they had managed to save 40% on the normal heating and ventilating costs. That represented a considerable sum of money. By making proper provision for services and sub-trades there was a chance of saving money on a broader front. This would become increasingly important as the years went on because the structural cost of a whole building was likely to decrease and the costs of central heating, air conditioning, and lifts in particular, would increase probably to approach the American proportion where the structure could be as little as 10% of the cost of a building, and probably averaged 20%.

Mr M. W. Low (Engineer, Ove Arup & Partners) had had occasion in recent months to design a building similar to that shown in Fig. 20, but with some significant changes. It was rather wider, the spans being 35 ft, 45 ft, and 25 ft, instead of 27 ft, 35 ft, and 27 ft, and was somewhat higher, having a first-floor slab in the outer bays. The crane was only 5-ton capacity, and the first-floor slabs projected as balconies about 6 ft into either side of the centre bay. This job had been designed four times—an unusual procedure, but there had been a reason for it—three times in steel and once in reinforced concrete.

185. The result was interesting. The reinforced concrete design (cost 100) was cheapest by 17%. That might not sound surprising, but the steel designs had all been uncased, and an uncased steel job might be expected to be cheaper than reinforced concrete. The three steel designs consisted of a conventional design to B.S. 449 (cost 123), a design using friction-grip bolts (127), and a rigid-plastic design with some composite action (117). The friction-grip bolt design had been much more expensive than any of the others, but when better design methods became available in Britain the position might be altered.

186. What effect had the height of multi-storey buildings on the relative economy of

reinforced concrete and steel? Steel might be cheaper, even though cased, at a height of 30 to 40 storeys.

187. In contrast to a previous speaker, Mr Low had found that his composite designs for steel beams with slabs over, were smaller in structural depth than simple construction. This saved considerably in cost of walls and services.

Dr K. Hajnal-Kónyi (Consulting Engineer in private practice) commented on the type of construction dealt with in § 28, where the Author came to the conclusion that for a roof frame of 50-ft span trusses at 10-ft centres were more economic than at 15 ft. That was based on simply supported purlins, but Dr Hajnal-Kónyi wondered why it was not usual in Britain to use hinged purlins, which were a feature of design on the Continent. The principle was that with a multiplicity of bays the purlins were not simply supported but hinges were introduced, which allowed for many variations according to the number of bays, and it was easy to choose equal bending moments in the spans and at the supports or equal deflexions with the exception of the bays.

With the formula for bending moment represented by $\frac{wl^2}{16}$ as compared with $\frac{wl^2}{8}$ the weight of the purlins went down very considerably, but the cost of erection was slightly higher. This form of design was not popular with structural steel firms in Britain, but in competitive tendering it was still possible to save a substantial amount of money. With such an arrangement the most economic spacing of the trusses would go up considerably.

189. He referred to the large-span construction shown in Fig. 15, with spans of 130–200 ft. There was a new form of construction which had originated in Germany, and of which there were already a few examples in Britain, known as the Silberkuhl* system. Had the Author considered it? It was based on composite action between a light lattice steel frame, which was post-tensioned, and concrete shells. The two materials acted together in a very efficient way, and the system allowed the suspension of cranes of 5 or 10 tons. It was a north-light roof. This seemed to be a form of construction which should be included in a comparison such as that in Fig. 17. It had the advantage also that the spacing of the glazing was about half that in design 6 of Fig. 17, and with a north-light roof a 50-ft spacing was not very efficient for lighting and 25 ft was better.

190. He referred last to multi-storey concrete structures, such as were shown in Figs 21 and 24. In future where the circumstances were favourable and there was easy access and flexibility for a crane such buildings could be erected with precast columns in one lift 50–60 ft high. He had had some experience of this and had found that with suitable cranes it was a very quick process and shortened the time on the site very considerably, because the casting could be done while work on the foundations was going on and connexion between beams and columns offered no difficulty. There were many ways of doing it, and it could be done quickly and economically.

Mr E. G. Trimble (Senior Engineer, Ove Arup & Partners) said that it should be noted that in the building to which Mr Low referred, which had been designed four times, the total design load of the first floor slab was 160 lb/sq. ft. With a smaller and therefore more normal load steel would be more competitive compared with concrete.

192. The British Transport Commission attached a figure of $\frac{3}{4}\%$ to the maintenance of steel structures and $\frac{3}{8}\%$ to the maintenance of concrete structures, both reinforced and prestressed concrete. For a 40-year period this amounted to 30% and 15% of the capital cost respectively. On the B.T.C. figures, therefore, there was a saving of 15% in favour of concrete (reinforced and prestressed), even when the capital cost for steel and concrete were the same.

* For a description of the Silberkuhl system see: Engineering, vol. 186, July–Dec., 1958. pp. 586–7.

Mr Ivan Collin (Senior Engineer, Taylor Woodrow (Overseas) Limited) called attention to the statement in § 12 that in general the cost was lower when more columns were used. Had the Author had any statistics to show increased foundation costs when more columns were used? Mr Collin had found on certain types of structures, that in using more columns, superstructure savings were sometimes outweighed by increased foundation costs, especially on low bearing soils.

194. Would the Author give a comparison of the estimated costs of alternative types of foundations which may have been considered in the project stage, for example, the costs of piled as against raft foundations before the final building design is adopted? On some soils the foundation cost could be a high percentage of the building cost. Recently Mr Collin had been associated with a tender for a chemical storage building 600 ft long by 90 ft span, specified to be constructed as a reinforced concrete arched rib structure, 50% of its cost was for the piled foundations on poor soil.

The following contributions were received in writing.

Mr F. R. Bullen (F. R. Bullen & Partners, Consulting Engineers) suggested that no single material possessed all advantages. Each structure was entitled to its own objective consideration and each structure would then be found to have a most economical medium for building. Whereas structural steel may be the most economical medium for one structure, reinforced concrete might be more economical and even better adapted for another. Also, timber was now being used for structural shapes as well.

196. Mr Bullen emphasized that a scheme would not be approached with any preconceived notions for such preconceived ideas made impossible objective analysis of the problem. Perhaps one advantage of having the advice of an independent engineer was just that. We could choose the materials and the layout best suited to the problem. In § 14 the Author referred to "amenities and open planning" and here again it was very easy to commence design with the preconceived belief that large spans were essential; as the Author had said: "an open grid can be a somewhat expensive hostage to posterity".

197. There were other factors involved in the economics of framed structures which lay beyond the mere structural form. For instance, maintenance costs could be very high so that design considerations should include proper reference to maintenance costs. Mr Bullen had suggested elsewhere¹ that the maintenance of portal frame steel buildings could be as little as 60% of the maintenance of the roof truss type. This referred particularly to single-storey structures but it was an important consideration. § 40 drew attention to the importance of maintenance, but Mr Bullen was puzzled by the fact that precast concrete could compete with steel. Surely the merit of concrete lay in continuity of structure which was very difficult to achieve in precast concrete. Could it be that the best use was not being made of steel?

198. Likewise, heating and ventilating as well as artificial lighting might have important bearings upon structural form. By eliminating members in the roof space and replacing the roof structure by portal frames it was often possible to lower the roof line and therefore to reduce the cube of the building; thus the heating and lighting installation costs and therefore maintenance costs could be materially reduced. If it be borne in mind that heating and lighting might account for as much as one quarter of the total cost, then it would be seen how important this consideration was.

199. By-laws required that a roof of less than 10° slope should be treated as flat and designed for greater loadings, than a roof whose slope exceeds 10°. Having regard to the need for reducing the cube of a building to a minimum, it followed from these two considerations that roof slopes of about 15° ought to be the most economical and that had been Mr Bullen's experience. Such low slopes, however, made difficult the use of trusses and it was on this account that portal frames had been found to be very competitive. The maintenance costs were reduced as well so that portal frame

¹ F. R. Bullen, "The single-storey factory and the rigid frame." *Struct. Engr.*, vol. 27. (Jan. 1949), p. 1.

construction with its greater elegance and reduced roofing costs was a very economical method of building single-storey buildings.

200. The Author's reference in Fig. 7 to a 5° roof was a little puzzling. It should be preferable to increase the slope to 15°.

201. Fig. 5 showed that lattice-type portals were cheaper than bolted trusses, but was the comparison true? Mr Bullen assumed that the columns were not fixed at their foundations so that, structurally speaking, the roof truss design shown had no lateral stability. Many buildings were put up in this way which relied upon the restraint of the floor construction: if the floor were removed they would collapse. On the other hand a portal frame was inevitably stable against lateral forces even if the feet were hinged and on that account it had an appreciable advantage over the simple truss design. Such a comment did not apply to the truss shown at the bottom of Fig. 7 which could be rigidly attached to the columns and thus might be safe against lateral forces. Fig. 18 also raised these points and Mr Bullen doubted, in fact, whether a portal frame was more expensive than simple trusses and columns.

202. There were limitations to the portal frame. There must be, inevitably, a horizontal thrust at the feet of the columns and in certain cases that could present problems. The problems affected the foundations and it was a mistake to think that the most economical superstructure necessarily produced the most economical building. For both single-storey and multi-storey structures, the Author concluded that structural economy was achieved by carrying loads to the ground as directly as possible, and that might be generally accepted. But if the ground conditions were very bad, necessitating special methods such as piling, economy would be better served by grouping the foundations, i.e. by opening out the columns. If, on the other hand, the ground conditions were intermediate in nature, then a multiplicity of supports with consequent smaller column loads would result in economy. If the ground conditions were poor at the surface but rock-like about 10 ft down, then large foundation loads would be called for and consequently wider column spacings would lead to overall economy. He submitted that however much care was bestowed upon the superstructure, overall economy came only from an overall view of the whole construction.

203. The Author had referred to foundations in § 69. It was very difficult, and, Mr Bullen suggested, not facing the facts, to consider as fixed a foundation resting upon the ground, unless the ground was rock. There must be movement, in rotation, to some degree which inevitably would affect the superstructure forces. But if the ground conditions were such that piles or piers were necessary or rock existed near the surface, then he agreed that the extra cost of providing fixity would be less than the saving in the superstructure.

204. True economy of building meant overall economy; and overall economy included the superstructure, but also it embraced the foundations, the general shape and maintenance.

Mr A. W. Hill (Deputy Director of Research and Technical Services, Cement and Concrete Association) noted that § 40 stated that reinforced concrete was not generally competitive in first cost with lattice steel for simple purpose-made shed frameworks except where standard concrete units were employed. Where considerable repetition was provided, as in many modern single-storey factories, economical solutions were possible with concrete units precast on the site, often with a minimum of shuttering since casting was carried out on the concrete floor. Considerable variation in individual requirements and shape of the roof form could be accommodated in that way at competitive prices.

206. Frequent reference had also been made to the high maintenance cost of steel-work. Could Mr Creasy indicate an average annual value of this item?

207. Mr Creasy had confirmed the considerable saving in multi-storey construction by the use of reinforced concrete. During the past few years very impressive speeds of erection had been shown with reinforced concrete multi-storey buildings—a storey a week being quite common. In reinforced concrete both steel and concrete were being utilized to their full advantage—with encased steel neither was fully employed. In

Britain 20-storey buildings had been successfully and quickly built in reinforced concrete, but abroad buildings had been constructed more than 400 ft high, and in a few cases more than 500 ft. Considerable development had also occurred with composite construction using both in-situ and precasting techniques in both reinforced and prestressed concrete. Mr Creasy's Paper had been written nearly a year ago and it would be interesting to have his views on trends in cost since then. Would he agree that the reduction in the cost of structural steelwork had been more than matched by the greater efficiency of concrete construction?

Mr G. M. Mills (Senior Lecturer, College of Technology, Birmingham) observed that the Author had stated in § 92 that the steel content was approximately the same for one-way spanning slabs for the same depth of construction. This was far too general a statement even bearing in mind that the majority of the two-way slabs compared in the Paper were presumably designed on the basis of the 1948 edition of the Code of Practice CP114.

209. The 1957 edition of the Code now allows for the design of rectangular two-way slabs on a load factor basis using Johansen's yield-line theory. The adoption of this method would result in considerable savings in steel compared with designs based on the use of the tabulated coefficients in CP114.

210. Fig. 45 showed the approximate weights of reinforcement for fully continuous slabs with similar spans for designs using load factor and elastic coefficient methods and expressed as a percentage of the steel required for one-way span in the short

FIG. 45

direction. The comparisons given in the Paper in tabular form in Figs 24 to 34 inclusive therefore appeared to require revision in the light of a possible reduction in cost of up to 10% by the replacement of one-way spans with two-way spanning slabs.

Mr J. R. Stanley (John Laing & Son Ltd) observed that the statement in §§ 93–94 that:—

“The cost of the beam will decrease with decreasing depth, the increase in the cost of steel being more than offset by the reduction in formwork and concrete.

Load-factor design has considerably assisted this tendency and for rectangular beams the ‘economic depth’ in terms of cost is one for which the compression steel approaches one-half of that required in tension,”

was in his experience not true.

212. It was important to get a clear understanding of the economic design of reinforced concrete members in isolation from all extraneous factors.

213. A design decision based upon such basic understanding could then be properly modified to take account of extraneous factors such as savings in cladding costs by using shallow beams to reduce storey heights. Such extraneous factors could often be very important.

214. Fig. 46 showed the economic design of a specimen beam related to effective depth, Q -factor, and several uses of the shuttering.

FIG. 46.—ECONOMIC DESIGN OF A BEAM OF NEGLIGIBLE SELF-WEIGHT

215. The solid lines were for a rectangular beam and the dotted lines for a T-beam.

216. The example worked was a beam:

- (i) Length 25 ft.
- (ii) Equal support and span moments of 1,800,000 lb/in.
- (iii) Concrete quality 3,750 lb/sq. in. at 28 days.
- (iv) Main reinforcement 30,000 lb/sq. in. in tension, indented bar, mostly straight bars.
- (v) Stirrups in mild steel.
- (vi) Load-factor design.
- (vii) $Q = \frac{M}{bd^2}$

The sections calculated had been chosen such that shear reinforcement did not affect the comparison.

217. Conclusions were:

1. In most cases, the cheaper design would fall within the areas shaded, i.e. no compression steel.
2. The uses of shutter was a most important factor. To standardize and make twenty uses possible would result in a saving of 40% of the cost of a rectangular beam or 30% of the cost of a T-beam for which one use of shutter only was possible.

218. The cost figures used in this comparison had been built up from current material costs delivered to site and a careful analysis of current labour outputs observed by work-measurement techniques within a contractor's organization; they were therefore the true cost of the work excluding overheads and not just the "bill rate".

219. The curves applied only in the case of a structural member where the self-

weight was a negligible proportion of the whole. In the case of slabs where self-weight was important it would be found that the cheapest cost occurred somewhat lower down the graph. Beams carrying light loads over long spans where self-weight was a high proportion of load would be cheapest using some compression steel in the design.

220. Because the percentage labour content in shuttering was far greater than in concreting or steel fixing it was there that there was the greatest scope for securing economics by the proper co-operation of the design and construction interests.

Mr J. J. Spyra (Partner, Taylor, Whalley & Spyra, Consulting Engineers) observed that when building up any formula it was usual to disregard all maxima and all minima and base formulae on an average, with a permissible variation up and down to a certain percentage. Despite the extreme cases mentioned in the discussion the Paper was a very useful guide, which, in some specific cases where labour and material ratio had a decisive influence, was restricted to England only.

222. The established fact that the right spacing of columns economizes the structure had been rightly stressed again, and it could not be stressed enough.

223. Mr Spyra's firm had just finished a comparison design for a warehouse with a 3-cwt superload on 14-ft $\times$ 14-ft grid (drop head slab). However, the owner had wanted an increase in span to 18 ft $\times$ 14 ft, and the steel required per square foot had risen from approximately 6 lb. to 8 lb. This was an increase of 33% in steel and approximately 12% in total structural cost. After a careful examination, the extra cost had not justified the increase in span and the owner had reverted to the 14-ft $\times$ 14-ft grid.

224. The Author had not given comparison data for a steel skin structure. Mr Spyra's firm had some data available for such a shed roof over a school workshop, spanning 40 ft, supported by continuous brick walls.

225. This structure consisted of almost vertical steel trusses at 15-ft spacing and specially strengthened Q-deck panels. The roof loading in this case was 31 lb/sq. ft including own weight, and the steel analysis was as follows:—

1. *Structural steelwork in roof*

$$(a) \text{ Latticed girder } \frac{1,526.38}{600} \text{ lb.} = 2.54 \text{ lb/sq. ft.}$$

$$(b) \text{ Fixing required for steel decking} \\ \text{(structural steel welded to main lattice girder)} \\ \frac{442}{600} = 0.736 \text{ lb./sq. ft.}$$

$$(c) \text{ Fixing required for glazing bars} \\ \text{(structural steel welded to lattice girder)} \\ \frac{302.5}{600} = 0.503 \text{ lb/sq. ft.}$$

$$\text{Total structural steel in one lattice girder} \quad 3.779 \text{ lb/sq. ft of floor area.}$$

2. *Steel decking in roof as above*

Robertson Thain Q-deck spanning 15 ft, type QDC, weighing 3.76 lb/sq. ft of horizontal area of

$$\frac{3.76}{0.968} = 3.88 \text{ lb/sq. ft horizontal area when at } 25^\circ \text{ incline.}$$

226. It had been suggested that the bottom tray be increased from 24-gauge plate to 20 gauge. In this case the weight of QDC decking would be increased to:

$$\frac{0.036}{0.022} \times \frac{27}{29} \times 3.88 = 4.4 \text{ lb/sq. ft horizontal area.}$$

227. When comparing these figures, it should be remembered that the total roof cover was in steel, and therefore a comparison with a truss and purlin structure had to be made with care.

228. The cost of the Q-deck panels, incorporating $\frac{3}{4}$ -in. insulation board and 5-ply felt roof cover, including complete steel structure, but excluding glazing bars and glazing, had amounted to 9s 8d/sq. ft.

Mr A. H. Brown (Frederick S. Snow & Partners, Consulting Engineers) observed that the Author had stated in § 44 that "fluctuations will be particularly dependent on market interests". When examining a relative cost factor performance between alternative frameworks of the order of 5–10% it was quite likely that selective competition for the manufacture was construction of the work might possibly outweigh certain aspects of design consideration, thus giving the engineer more freedom in his approach when viewing his problem from a commercial angle. In all structural undertakings it was important to study market interest since this might well eclipse finer design economics.

230. In § 34 the Author had made the point that a combination of tube and angle members in the right setting could make for an economic and efficient type of truss. The consideration of a combination of reinforced concrete and structural steelwork in single-storey buildings could prove to be expedient. In Mr Brown's experience it had been found that reinforced concrete columns were cheaper than their counterpart in structural steel; that was particularly the case if the building was to be substantial and clad with conventional materials rather than a shed with light covering. This was emphasized if a building was required to have a minimum 2-hour fire resistance where concrete was a suitable material to meet this requirement. There was a further attractive aspect with this form of composite construction whereby the main contractor would generally have a continuous programme in his work instead of a rather sharp break after he had completed foundation work and normally had to await the erection of the steel frame—such continuity contributed to an overall saving on building costs.

231. Undoubtedly cold-rolled sections when used correctly could be an economical material but were more expensive per unit weight of steel. However, these members were formed of relatively thin sheets and there was little margin should they suffer corrosion. It was appreciated that care would be taken before using such members in a corrosive atmosphere, but even a simple purlin in any building usually received its protective paint on the topside when it was erected, after which time it was usually impossible to paint it again unless, of course, the roof was taken off. Some of these members were phosphated or enamelled or both, but would they perform the same duty as the traditional hot-rolled section?

Mr Sidney Rosenak (Consulting Engineer) observed that the Paper made no mention of timber structures. Timber roof trusses and portal frames for medium spans would certainly be worthy of consideration and the figures given in Table 2 might therefore be of interest.

TABLE 2.—APPROXIMATE RELATIVE WEIGHTS AND COSTS OF STEEL ROOF TRUSSES AND TIMBER BOWSTRING GIRDERS

Span: feet	Self-weight: lb.		Cost per lb. of material: s	
	Steel	Timber	Steel	Timber
30	580	420	0.99	1.6
40	800	620	0.96	1.5
50	1,100	950	0.93	1.4
60	1,500	1,500	0.90	1.3

233. Apart from prime costs, other considerations such as fire hazards might influence the choice of a particular material. In this respect timber might be for superior to unprotected steel or aluminium in roof construction.

234. Had the Author any figures on various types of timber roofs which could be compared with steel and concrete roofs?

Mr J. Springfield (of Wallace-Carruthers Ltd, Toronto, Canada) was surprised to find, in a Paper dealing with the economics of structures, no mention of what had undoubtedly proved to be the most economic single-storey steel-framed building in use in North America. The type of building to which he referred had a flat wood or metal deck roof carried on long span steel joists (L.S.S.J.—standard lattice girders) framed into steel beams and columns.

236. Some years ago, the B.I.S.C. distributed reproductions of an article on this type of building which had been published, Mr Springfield believed in the “Manchester Guardian”. There were examples of this construction in Britain, but generally speaking, a large expanse of flat roof, devoid of natural lighting, seemed to be unpopular. However, since short hours of daylight in winter demanded an artificial lighting system adequate for continuous working, no great additional expense was involved. The problem of ventilation was little different from that which existed in the buildings under discussion in the Paper, while the waterproofing and insulation of a suitable deck were more straightforward than for sloping roof structures.

237. The Authors inferred that standard buildings were uneconomic. The L.S.S.J. was a standard building component, along with the smaller open web steel joist, which together covered spans ranging from 4 to 70 ft, ranging in depth from 8 to 36 in. They were as readily available as any steel beam, and keen competition in their manufacture ensured an economic price (their manufacture was not limited to steel mills).

238. The following unit weights were for an industrial building having a $1\frac{1}{2}$ -in. tongue-and-groove wood roof deck, felt and gravel roofing, designed for the lighter roof loads permitted by British codes of practice:—

- (i) 50 ft × 30 ft bay as in Fig. 3

L.S.S.Js at 7 ft 6 in. centres

Unit weight of joist 3.1 lb/sq. ft

(cf 3.3 for the combined riveted trusses and purlins or 3.1 for an all-welded truss)

- (ii) 50 ft × 20 ft bay as in Fig. 4

In this case the deck was not being used most efficiently with joists at 6-ft 8-in. centres:

Trusses	3.5 lb/sq. ft
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Valley beam	0.8
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Column	0.4
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4.5 (cf 4.8).

The valley beam weight was based on an alternate anchor span and cantilever-suspended span arrangement.

239. Clearly, the standard joists showed a greater economy over trusses when used for smaller spans. However, it was noted in this regard that there was a considerable difference between the unit weight for a 40-ft-span riveted truss from Fig. 1 (1.7 lb/sq. ft) and a bolted truss of the same span from Fig. 5 (4.7 lb/sq. ft).

240. The cost of L.S.S.Js was approximately 80–85% of the cost of riveted trusses, but obviously, this cost could only be achieved by fabrication on a production basis.

241. Would the Author explain more fully the term “hollow-slab” construction? Since it appeared to be equally suitable for one-way, two-way, and stepped slabs, and could be used in depths as shallow as 5 in., it must be quite different from Mr Springfield’s understanding of the term.

The Author said that the discussion had raised many points which were interrelated and he had accordingly grouped his replies under the following headings:—

General procedure

243. He had indicated in § 18 and elsewhere in the Paper that there were many factors of amenity and expediency which would justify the non-selection of the most economic form of structure for a particular project. It would always be important, however, to make the best possible assessment of the relative costs of the various alternatives so that the final choice might be as realistic as possible. The Paper was intended to assist in that process.

244. It had been suggested that variations in the form and planning of the structural frame would not exceed 4% on the overall cost of the work and were therefore not worth considering. If taken quite literally, this seemed a highly dangerous principle to adopt, and lack of care in the development of the framework would in many cases affect the overall cost of a project by a very much greater margin.

245. The basic problem was one of good housekeeping. The overall cost of a scheme was compounded of a very large number of small items. The structural frame accounted for by far the largest single item in the whole cost, and it was surely the engineer's responsibility to see that the money devoted to that work was spent in the most efficient manner.

246. A reference had been made to aspects of contractual procedure that affected the economics of design and construction. That subject covered a very wide field, and a full exposition was probably outside the scope of the present discussion.

247. A close integration of design and construction could be ensured by nominating a contractor at the outset of a project and associating the planning and execution at all stages of the development. Such an arrangement should make a positive, if somewhat indeterminate, contribution to the final economy.

248. Such procedure might obtain the maximum efficiency of the selected contractor but would not, presumably, ensure the selection of the most efficient contractor. It would seem to eliminate the important element of competition which ultimately measured all those indeterminate factors of construction techniques and organizational efficiency to which reference had been made.

249. Presumably one of the functions of the specialist engineer was to advise on these matters and to incorporate them in an efficient design which allowed the full economic advantage to be gained.

250. In that respect, probably the most important contribution to overall economy was made by thoroughly thrashing out and anticipating all aspects of basic requirement and subsequent development in the design stage, so that a complete set of working details and bill of quantities could be prepared which would allow the contractor to consider the cost of construction in confidence and absolute certainty of all the relevant conditions.

251. A number of contributors had provided and recommended further examples of framework. It was important to examine these by comparison with a conventional solution, and in many cases some guidance on this could be obtained from the information given in the Paper.

Current validity and future trends

252. The Author observed that some contributors had queried the relative cost factors of particular examples quoted in the Paper and had asked whether they were still valid or likely to change in the future. Those factors were the results of the analysis of specific cases deduced from tender quotations or average costing taken from the best contract experience available. The examples quoted were typical and could be taken as indicating trends in the general relative position. Those trends were frequently checked and had been found generally consistent. A particular case might carry special conditions and would not then conform to the general pattern. Unless all aspects of

such a case were known it was not possible to comment effectively on the reasons for such non-conformity.

253. There had recently been a considerable fall in the cost of steel framework, but that had been matched by an equally remarkable advance in the efficiency of reinforced concrete construction accompanied by a corresponding reduction in cost. In a recent example a reinforced concrete frame of beams, columns, foundations, and slabs, as constructed, had been compared with an alternative cased steel frame of commercial design and had shown a difference of 30% of the cost of the frame in favour of the former. The Author believed that such a marked relative cost advantage would not be easily overcome.

Foundations

254. In a comparison of the different forms of construction the foundations should be included where there were differences in the load or in the imposed restraint. In general, however, the influence of the foundation on the relative costs of the alternatives was small.

255. The economic choice of column spacing was not greatly affected by variations in the subsoil condition. The total cost of the foundations was broadly dependent on the overall load to be carried and the soil characteristics, and was largely independent of whether the same total load was carried in small or large concentrations.

256. A considerable depth of overburden could affect the spacing of block bases but in such circumstances this type of foundation was not, in any case, generally economic. For soils of low bearing area a foundation of piles or strip raft did conform to the general rule of being largely independent in relative cost of the degree of load concentration.

257. Where applicable, the strip raft would be cheaper than piles, and the virtues of the former were too often overlooked. In many cases of piled foundations the caps alone provided adequate raft support from which the piles were suspended.

258. A quite high degree of uniform settlement could be satisfactorily absorbed by a strip raft without noticeable inconvenience to the users, provided that the foundations and structure were of a form that was potentially capable of ironing-out any relative settlement. A large proportion of the initial settlement was absorbed during the construction period and prior to the occupation of the building, and the strip raft was potentially capable of safely absorbing any relative settlement should it develop.

259. In portal-frame workshop construction it was not difficult to achieve the necessary conditions for full fixity in the foundation. A rock subsoil was not essential, and in practice most clays satisfactorily provided the required restraint. The dead load usually provided a very small part of the deforming force on the foundations. In terms of foundation restraint, crane and wind loads were of intermittent and short duration and were therefore less likely to induce long-term permanent yielding.

Reinforced concrete versus steel

260. The Author observed that contributors seemed generally agreed on the economic advantage of the reinforced concrete frame over the cased steel frame. In multi-storey frame construction the reinforced concrete work was originally used in the same form and as a direct substitution for the cased steel frame. The former had, however, now developed a flush-slab form without projecting beams which was very economical in space, weight, and cost, and possessed special advantages in planning and adaptation. He could not visualize conditions in which the cased steel frame could easily recapture its former predominance of use in such forms of construction.

261. Reference had been made to the conditions which, it was claimed, favoured the adoption of the cased steel frame. In practice none of those conditions was sufficient to render cased steel cheaper than reinforced concrete.

262. On a confined site the storage and mixing of concreting materials might be inconvenient, but the volume of concrete required for the cased steel and reinforced

concrete frames were approximately equal. No other building operations could be carried out while the steel frame was being erected, but such a restriction did not generally apply to reinforced concrete work. The solution to the confined site was generally found in the use of ready-mix concrete, or in the use of a precast frame which carried all the advantages of steel prefabrication—extended to include the casings.

263. A characteristic of reinforced concrete was its flexibility; this form of construction was well adapted for economic use on irregular sites, and structures with awkward set-backs.

264. It was a fundamental requirement of economical construction that all concerned should “know what they wanted”. Nevertheless, reinforced concrete was probably more convenient than steel in providing for late second thoughts immediately prior to actual construction.

265. When the frame was complete drastic alterations to it would call for ingenuity in both cases. The technique for each was generally quite different, but reinforced concrete was certainly not at a disadvantage. Practical devices included the use of welded stop plates to existing reinforcement to provide for an extension of the framework, the stiffening of members by corsetting or grouting additional reinforcement, and the insertion of slings and trimmers to form new openings in existing slabs.

266. Several contributors had referred to cases in which reinforced concrete appeared to be cheaper than an uncased steel frame. That distinction would probably disappear if the schemes were submitted to competitive tender which allowed the most economic use of the steel framework. A lattice frame often showed to advantage.

Reinforced concrete construction

267. A number of references had been made to the “economic” depth of reinforced concrete beams in terms of the actual cost of the work, and there seemed to be general agreement that shallow construction reduced the floor-to-floor height of the structure with ancillary cost advantages which followed from a reduction in the cladding and in the provision of services.

268. In the reinforced concrete beam the cost of the steel reinforcement, the concrete, and the formwork were each approximately equal to one-third of the overall cost of construction. A reduction in depth lowered the cost of formwork and concrete at a greater rate than the increase in steel. The Author found that, in general, the practical limit to a reduction in depth was controlled by the arrangement of the reinforcement, particularly at the junctions with the columns. The depth of the reinforced concrete beam need not generally be deeper than the cased steel beam, but it would generally be wider.

269. In the design of the normal reinforced concrete structure the beam effectively combined with the slab at the centre of span to form a T-beam but was confined in practice to a rectangular box section at the ends to carry the negative restraint moment over the column supports.

270. For maximum economy the beam section must be without haunches and of constant section throughout the span. The depth of beam was controlled by the shear and moment at the support and might be reduced to a dimension at which the compression steel at that section approached one-half of the tension steel, without incurring a cost penalty. The combined concrete section available at the centre of span and the reinforcement required followed from these conditions, but would not then generally require compression steel at that point.

271. In this context the diagrams of Fig. 46, relating to the economic depth of T-beams, appeared to be based in design on a constant T-section throughout the length at both mid-span and support, and therefore had little practical significance.

272. The conclusion based on time-study, that multiple repetition would considerably reduce the cost of the work, was valuable. In practice the cost advantage was not always passed on to the client; but that lent very strong support to the plea that had been made for a universal range of standard beam and column sizes, in which variations in

strength would be achieved by different bar arrangements in the same concrete section.

273. Reference had been made to the precast concrete frame and to its use in special circumstances. Precast work was generally of the same order of cost as the alternative cast-in-situ frame, but the former sometimes carried a cost penalty where the units were executed off site, depending on the distance over which they were transported. The relative economics usually depended on the cost of transport and on the simplicity of making the site joint. For the multi-storey structure the precast work had the disadvantage of not being easily adapted to flush-slab construction.

274. The equitable balancing of one-way and two-way slab design was a very complex operation. Examples shown in the Paper were arranged to illustrate the economic advantage of using two-way spans where the supporting beam frame was constructed to an approximately square grid, and where by so doing the depth of construction and dead weight could be reduced. In other circumstances there was no economic advantage to be gained generally from the use of two-way span design.

275. In the design of continuous slabs spanning in one direction it was usual to assume a "live" arrangement of the superimposed load, whereby the induced moments were based on the most severe conditions of adjacent or alternate spans loaded. This was a condition very much more severe than that based on "dead" load uniformly distributed on all the spans.

276. Slabs spanning in two directions were commonly designed from the Code by elastic coefficients applied to the free span moments. Without closer manipulation those coefficients were based on "dead" load conditions and were generally suitable for relatively lightly loaded commercial structures. When calculated in that manner the sum of the induced moments in each direction would be approximately equal to the total moment calculated for a similar slab spanning in one direction only.

277. The diagrams shown in Fig. 45 relating to the elastic design of floor slabs appeared to compare a two-way spanning slab carrying "dead" load with a one-way slab subject to "live" loading. In such a case the conditions were not comparable and that was not a valid economic comparison.

278. Conventional methods of design applied to reinforced concrete produced in general a structure that would safely carry a much higher load than that indicated by theoretical calculations; in this respect floor slabs were probably worse offenders than other units in the frame. The problem would be satisfactorily resolved only by the comprehensive load testing of full-scale structures, and this presented many obvious difficulties. The Author was engaged on a long-term programme of such full-scale tests on floor slabs, and he had found that the steel content of both one-way and two-way slabs calculated by conventional means could be considerably reduced with safety.

279. In this respect the yield-line method of floor slab design gave some advantage, but was only simply applied to square slabs where it resolved itself into an adjustment in the modifying constant of the free-span moment determined by an elastic design. The application of that method to the two-way slabs on a square grid as illustrated in the Paper would tend to emphasize their advantage, but would not generally affect the advantage of one-way slabs on rectangular panels.

280. The term "hollow slab" referred to an in-situ concrete slab formed with hollow clay pots. The latter were commonly 12 in. square and $3\frac{1}{2}$ -12 in. deep, and were normally provided with open ends and laid end-to-end to form a hollow channel between narrow ribs. These were cast integrally with a thin concrete topping approximately 2 in. thick laid over the pots to form a flush slab top and bottom. For a two-way spanning slab the open ends of the pots were sealed by a sheet-steel strip, or by other convenient means.

Single-storey framework

281. In single-storey buildings the incidence of the lateral forces from wind or equipment was generally much greater than that from dead load, and reference had been made

to the alternative use of truss-on-post and portal frames for such structures. A distinguishing characteristic of the two types of structure was the means by which the lateral forces were supported, but the use of the terms was not precisely defined and considerable overlapping in function was possible.

282. With the truss-on-post form of construction the lateral forces could often be conveniently carried to the ground by bracing, and this, in general, was the most economical form of frame. Where the height and span was short, the bending at eaves or base was small and the usual shoe fixing or block base provided sufficient restraint without additional stiffening, so that each frame was then, in effect, a self-contained portal.

283. Alternatively, for larger frames a knee brace could be introduced at eaves level and the foundation could be stiffened, but in this form the frames continued to act as portals, while retaining the appearance and economic characteristics of the latticed truss-on-post.

284. The solid-web pitched portal frame was attractive in appearance and had the advantage of providing additional clear space above the eaves at centre of span. In practice, however, it was rare to find that that additional space was effectively used, and the Author had found that the solid-web portal was generally somewhat more expensive than the alternative lattice frame.

285. The cost ratio of 4:5 which had been indicated in the Paper for simple and complex fabrication referred to the relative overall costs of types of construction of which the welded solid-web and bolted-truss framework were respectively representative. This ratio had been deduced from an examination of recent contracts and had been suggested as an average guide which it would be worth while to cross-check for an important specific case.

286. It was hardly possible to make an effective comparison between the framework indicated in Figs 17 and 43, since these referred to structures of very widely differing spans. It would be of value to compare the cost of the 100-ft span with an alternative latticed form of construction.

287. For the smaller simple buildings of common standard dimensions, precast concrete frames could be purchased from stock, and they were often very competitive in cost with unclad steel. This applied to a manufacturer's standard item where costs were greatly reduced by a high rate of re-use of formwork. To retain their competitive advantage such frames must be used in the standard form as sold and without alteration, and as such compared unfavourably with the flexibility in planning provided by the unclad steel framework.

288. The truss of 5° pitch was efficiently formed with a deep shoe, as shown in Fig. 7. Such a frame was cheaper than one of the conventional pitch of 25°. The roof covering for the shallow slope was more expensive than the common 6-in. corrugated sheeting, and some additional side cladding was required above bottom tie level. The overall costs of the complete frame and cladding for the two cases were similar.

289. All forms of large-span roof structures were commonly arranged as a combination of main and one or more secondary systems of framework. Such systems in which the total load was carried more than once were potentially less economic than single-frame systems.

290. Low costs were normally achieved by reducing the cost of one of the systems, with a relatively smaller increase in the cost of the other. For maximum efficiency the centres of the main frames or trusses would not be common for all spans, and truss centre and truss span would vary with the unit cost of truss and purlin fabrication. The actual unit cost of simple joist or angle-purlin construction should be much less than that of the truss fabrication, but in practice such a marked distinction in relative rates was not effectively reflected in the overall unit cost rate of the framework.

291. On that account there seemed, generally, a practical economic advantage in reducing the relative cost of the purlins by closing the truss centres or by using long-span purlins of lattice or light-weight form. The latter solution would be used generally

for the larger spans. In an important case it would be worth while to check the correct proportions.

292. Cold-formed fabrication was very economical when used for standard units or with a high degree of repetition. Such units were most efficient when employed as secondary units, such as purlins, in combination with conventional framework of hot-rolled sections. Modern protective methods were effective in ensuring a useful life that was comparable with the useful life of hot-rolled sections in normal atmospheres; they were not perhaps so readily available in Britain in standard units which could be effectively used for floor construction. Purlins were normally designed by Code rules which allowed for conventional conditions of continuity.

293. Comparing the unit weights for 40-ft span trusses, as indicated in Figs 1 and 5, the former referred to separate truss and purlin units. The latter included the framework for the complete building.

294. The efficiency of the rectangular-column module for steel-frame construction was illustrated in Fig. 10. The frame of rectangular grid covered a clear area 50% greater than that of the square frame, without a cost penalty.

295. In the example of hangar building construction shown in Fig. 14 the figures for weights and their relative percentage referred to the steel or aluminium content only, either in sections or in reinforcement as appropriate to the form of construction.

296. The aluminium framework shown in Fig. 14 comprised truss units with a high degree of repetition and arranged to suit the requirements for maximum economy. It would not be difficult to select an example in which the light alloy fabrication carried a much higher cost penalty.

297. Timber framework, and especially laminated timbers, would be found generally more expensive than construction in steel. Table 2 appeared to confirm this.

298. The Silberkuhl roof was most attractive in appearance but must be expected to be rather more expensive than a latticed steel frame with asbestos covering.

Composite construction

299. The Author recalled that a number of references had been made to the overall economy which could be achieved by combining in one framework units of different materials and types. He fully agreed with that general principle, of which many potential applications were to be found. That question was, however, greatly affected by market interest, and in many cases industry was not organized to allow the full economic advantage from composite construction to be achieved.

Multi-storey structures

300. In the recent past the capacity to build tall structures was thought to be restricted by the foundation conditions, and multi-storey structures were limited in height to about eight storeys. Those structures were generally of cased steel-frame construction, but so far as could be seen in retrospect, there was even then no economic justification for the use of that medium.

301. By the use of spread foundations structures of twenty storeys were now successfully being built, and on economic grounds the growing tendency was to construct these in reinforced concrete. An important feature was the use of flush floor slabs which showed many improvements in amenity and planning generally.

302. In a steel frame the flush-slab effect was produced by a false ceiling to the beam structure, with corresponding increase in the depth of construction and loss of floors for a given overall height of structure.

303. In the reinforced concrete flush-slab structure lateral forces due to wind were normally carried to the ground by the horizontal and vertical diaphragm action respectively of the floors and wall panels of the end bays or stair wells. In the steel frame the contribution of such a membrane action was commonly ignored, and the horizontal forces were carried by elaborate connexions at beam and column which were themselves formidable cost-raisers.

304. In order to increase the height of a building which could be safely supported, the effective carrying capacity of the subsoil could be further increased by the use of a basement structure of cellular-raft form extended as necessary beyond the confines of the superstructure above. In that manner buildings of forty and more storeys could be constructed on the types of subsoil commonly met in Britain. For such structures the floor slab and framing at all levels would be more economical if constructed in reinforced concrete. The lower lengths of the columns if in reinforced concrete would be large and would tend to encroach on the useful space.

305. As the industry was organized at that time, the normal solution would be to construct the lower portions of the frame in cased steel, and as a contribution to economy the upper section might be in reinforced concrete. That seemed, however, another example where costs might be reduced by a composite form of construction, and the economic answer might well be to incorporate cased steel columns for the lower lengths in the reinforced concrete flush-slab form.

Maintenance

306. One of the intangible factors to be considered in balancing the merits of alternative schemes was concerned with their long-term serviceability and the probable annual expenditure on necessary maintenance. The attention required was greatly dependent on the local conditions. For internal work in normal atmosphere, a well constructed reinforced concrete frame would not generally require maintenance unless this was required by the pattern of decoration. In similar circumstances an exposed steel frame would require painting in the early years, but when a deep paint film had been formed the maintenance period could be greatly extended, except as required for decoration.

307. For exposed work, the Author would expect that the reinforced concrete frame might require some repairs in the cutting out and re-grouting of cracks and other defects as they appeared. The exposed steel frame would require much more regular attention if the strength of the structure was not to deteriorate.

308. In order, effectively, to bring the incidence of maintenance costs into a comparison of alternative schemes an attempt must be made to convert them into a lump sum. For that purpose a forecast would be made of a probable maintenance programme, the annual cost of which could be compounded into an equivalent capital sum by actuarial manipulation. In a recent example of a hangar building which had been considered in alternative schemes of latticed steel frame and reinforced concrete, the annual maintenance charges were assumed to amount to 1% and $\frac{1}{4}$ % respectively of the initial total cost of the work.

309. There were so many uncertain factors in such an exercise that the answer could usually be adjusted without much difficulty to produce any required result. In most cases the fairest procedure was to ignore the relative expense of maintenance, and to base the assessment on first costs alone.