Aluminium Structures—General Aspects of Design

S. K. Ghaswala

ONE of the indices of gauging the industrial expansion of a nation is through its production and per capita consumption of valuable materials. In this connection comparisons between steel and aluminium appear quite revealing. While steel, because of its valuable physical and engineering properties, has so far dominated the world as the ruling metal of this modern age, the claims of aluminium, cannot be overlooked or sidetracked. In 1959 the estimated world production of steel was 314 million metric tons, which represented an increase of 97% in world output over the 1949 figure. During this 10-year period aluminium production increased from 1,184,000 metric tons to 4·1 million metric tons, that is 246%, or nearly 2·5 times the rate of growth of steel. For an equitable comparison on a volumetric basis the 1959 figure for world production of aluminium works out to 11,497,000 metric tons or 3·7% of world steel production. On the domestic side the country's production capacity just prior to Second World War was 3,000 tons, while by the end of 1959 the annual primary capacity of aluminium had reached 18,100 tons. This production is not at all sufficient since the country currently spends nearly Rs. 200,000 daily for procuring the metal from abroad. It is therefore very necessary to stop this drain on an already weak foreign exchange situation.

On the actual consumption side taking both the imported and indigenous volume, India's per capita consumption of aluminium comes to 0·274 lb (0·124 kg) as against 29·5 lb (13·38 kg) in U.S.A ; 16·5 lb (7·5 kg) in Switzerland ; 15 lb (6·8 kg) in U.K ; 13·5 lb (6·1 kg) in Canada : 10·8 lb (4·9 kg) in Sweden ; 10·36 lb (4·7 kg) in West Germany ; 7·94 lb (3·6 kg) in France ; 7·6 lb (3·45 kg) in Australia ; 3·7 lb (1·68 kg) in Italy ; and 2·4 lb (1·089 kg) in Japan. This clearly brings to light that in spite of the long leaps taken by aluminium in this country, the critical productivity figures are still extremely low.

If the country's production is to increase to 82,500 tons by 1965-66 as envisaged in the Third Five Year Plan, the per capita figure will increase proportionately. Assuming the population to reach 480 million in 1965-66 as estimated by the Central Statistical Organisation the consumption will be 0·385 lb (0·175 kg) per capita, that is about 1·4 times the current figure. Even this consumption judged by world standards, is appreciably low. In fact these figures become more striking when it is realised that the per capita consumption of steel is at present 156 lb (71 kg) that is nearly 570 times the aluminium consumption, and with the new steel plants coming up this gap may widen further.

In view of the fact that India possesses abundant bauxite reserves, estimated at over 250 million tons, of which over 25 million tons are considered very suitable for the production of aluminium, it is imperative that more and more attention be devoted to this light metal. Aluminium costs about 40% more in this country than in the Western nations, but with increased know-how and production facilities and expansion of other industries, this difference may ultimately dwindle down. Another aspect is that the capital cost requirement of steel per ton is of the order of some Rs. 1,000 ; whereas it is in the vicinity of Rs. 10,000 per ton in the case of aluminium. By the adoption of larger smelters this difference can also be reduced. Thus the production cost for a 50,000 ton smelter could be 20% less than for a 20,000 ton smelter. On the other hand, aluminium has its own special value when it comes to replacement of other metals. For example, out of the estimated consumption of 100,000 tons of copper per annum in India, about 25,000 tons could be replaced by the light metal and out of 34,000 tons of lead consumption, over 6,000 tons could be replaced by aluminium, with overall economy.

The author has found that in the production and use of aluminium, a strange disparity exists in the extraction and production technology on one hand, and design and fabrication techniques on the other. Thus marked improvements have been made in the Bayer process plant in the washing, filtration and calcination operations.

Manpower requirements have been reduced from 25–30 man-hours to nearly 8-10 man-hours per ton, the power consumption has been reduced from 22 to 18 kW per kg of aluminium produced, and the purity of the metal raised to 99·98 per cent. On the other hand a comprehensive understanding of the principles of design and fabrication is yet limited, since most of the construction carried out has been a mere copy of steel designs. Little consideration has been given to the specifically differing properties of the light metal and their impact on design fundamentals and the consequent economics of application.

Mr. S. K. Ghaswala, B.E., M.I.E., M.I.I.M., M.I.Ae.S., M.ASME., F.ASCE., M.Soc.C.E. (France), M.Inst.M., Consulting Engineer, Bombay.

Basic differences

The necessity of correctly gauging the utility and efficiency of light alloys stems from the fact that there are certain inherent differences in ferrous alloys and aluminium which affect their overall design aspects. These are discussed below :

(*a*) Basically iron has a body-centred cubic crystal structure, while aluminium has a face-centred cubic structure.

(*b*) Aluminium has a density and elastic modulus nearly one-third of steel, although its strength is of the same order as steel for some of its alloys. In view of its low elastic modulus and the use of thin-flanged sections problems in elastic instability in various forms assume importance. This is not the case in steel, where due to the limitations of the rolling process the flanges of normal steel sections are comparatively so thick that instability due to buckling is rarely considered.

(*c*) Aluminium is virtually completely resistant to atmospheric corrosion and as such sections can be made very much thinner than those in steel.

(*d*) In steel there are only a few limited standard structural sections with which a designer works, such as I, Channel, Angle and Tee. Aluminium sections are produced by extrusion in addition to rolling process and permit the use of a very large variety of sections. Very often it becomes quite economical to extrude special sections for particular conditions of loading and stress. Form strength and shaper-economy thus assume greater significance in aluminium than that in steel.

(*e*) On a volumetric basis aluminium costs much more than steel because of the inherently high production costs. It is, therefore, logical to effect as much economy in the use of the light metal as is rationally possible. On the other hand, aluminium fetches a comparatively high scrap value than steel—a fact which should be given consideration in cost analysis.

These are the most conspicuous differences affecting the structural engineering field, although other design characteristics have also to be given their due share of importance. Among these are fabrication aspects, safety factors, fatigue, and thermal and electrical properties. However, what is essential is to conceive the fact that aluminium is a metal different from steel and the design approach should, therefore, be based on these differing characteristics to achieve the maximum economy.

General design principles

Aluminium as already pointed out is a very expensive material and, therefore, requires to be used very carefully so that its full area or volume is stressed to the maximum possible extent. Methods of use, whereby this principle can be achieved are briefly discussed below :

(*a*) *Compression:* In the case of compression members, angles are prone to torsional buckling but rarely to local buckling. A root fillet is generally introduced in the extruded sections of this form to increase their torsional stiffness. Further, single unequal angles are inferior to equal angles and should be used very sparingly and only when other forms cannot be used. Double angles riveted back to back or in cruciform section increase the overall efficiency. Bulb angles also increase the torsional rigidity very much and become economical when used for light and medium latticed structures.

In the case of single channels whose web to flange-length ratio is more than 2·5, flexural buckling about the y-axis or local buckling will govern over the entire slenderness ratios, but as the flange is increased, failure due to combined flexure and torsion assumes importance. Two channels back to back are relatively strong and rarely fail by torsional instability unless the flanges are very wide and thin. Lipping of such flanges can increase their resistance. For predominantly heavy axial loading battened channel struts are useful.

H-type sections have a fairly high overall resistance, except when they are very broad and thin when they are likely to fail in torsional instability. By adding bulbs and/or lips this type of failure can be either overcome or reduced and the strength increased. Lips are more effective in resisting local buckling, whereas bulbs increase local as well as torsional resistance.

Closed sections are on the whole superior to open sections and need not be examined for torsional instability. In the case of braced struts, it is advisable to use a light channel section for bracing instead of the usual flats adopted in steel design. The flanges of such a channel section considerably increase the stiffness and render the bracing very effective. Such bracings are designed to withstand a total lateral transverse shear force of magnitude equal to 3·5% of the total endlong compressive load together with the shear force resulting from external loading.

(*b*) *Flexure:* The ordinary I section is commonly used for beams in light alloys and is fairly economical. Bulbed I sections are utilised when high flexural and torsional rigidity is demanded. Diagonal bracing members can be conveniently designed with I sections, especially where double-member chords are being used. In such cases when they are used as struts the sections should be squat so that their momental ellipse is more circular than for ordinary I beams. For lateral instability extruded thin-webbed I beams can be used. They are, however, expensive and under suitable conditions of stress and loading can be replaced by fabricated box beams.

Channels and Z-sections, because of their lack of symmetry, twist and sway, when normally used as beams. They are, however, useful as secondary stress members as in roof purlins. In such cases care should be taken to see that they are so loaded that the line of action of the applied load passes through the shear centre on channels or is inclined to oppose the lateral movement in Z-sections. Generally by using them in pairs these difficulties can be overcome. The most convenient proportions in this condition are for the depth to be twice the width. Channels are available with lips, and are then known as "top-hat" sections. Such a section can be used as a web stiffener or in combination with plates it can be used to form a double-webbed girder or a strut. Minimum thicknesses in this case are usually governed by the extrusion process and sections with webs having a depth to thickness ratio of about 30 and flanges having a width to thickness of about 15 appear to be the thinnest that can be readily manufactured.

As a very broad generalisation it can be said that without any stiffening, equal angles are prone to torsional instability with a leg thickness ratio of 12. With the introduction of bulb and fillet this ratio can go up to 20. Such sections can be used in lattice works when the slenderness ratios are over 50. While details of bulbs and fillets required for each section depend on the precise type of sections and nature of stresses, it is found that bulbs having 3t diameter and fillets having 3t radius (t, being the thickness of the section), are just about right to prevent torsional faliure at slenderness ratios down to 60.

Unequal angles used in pairs are perhaps the most economical for lattice type structures especially when used so that their lengths are in the ratio of 3 : 2 and the ratio of longer leg to thickness is 20 : 1.

Unconventional applications

In structures where strength is of primary importance, high-cost, high-strength, heat-treatable alloys appear favourable, while low-cost, low-strength alloys give economical results when used for slender compression members and also where deflection is the guiding criterion. In light-weight design, important considerations arise in different types of structures, which can be broadly subdivided into two classes.

The first is s set of complicated assemblies and lattice structures wherein the maximum permissible stress rather than stiffness or deformation is the governing factor. The second class comprise long and slender tension and compression members as well as thin-walled sections, where secondary stresses due to elastic instability and crumpling assume greater role than principal bending or compressive stresses. It is very essential to realise that in aluminium structural design the shapes and forms of members considerably influence their load-bearing capacity. Based on Thum's theory of form strength, it has been shown that a member must have such a shape that the material of which it is made has a minimum volume at points of low stress and this volume is virtually non-existent in and around the neighbourhood of neutral zones. Further, stress concentration should be avoided as far as possible. Latticed structures and thin-walled sections extruded in special forms come very near to this ideal if rationally designed.

Stressed skin construction as adopted in aircraft structures offers wide potentialities in building design if intelligently utilised. Thus the roofs forming outer covering could be made out of aluminium sheet, which unlike conventional design, would also carry a part of the roof stresses normally carried by a truss. The whole roof unit then acts as an integral section where all members are fully stressed and the necessity of having roof trusses is eliminated. Some of the European rolling stock have made use of this principle in their carriages. Going a step further, the roof truss, if at all used, could be designed differently by employing a bench-like section. This peculiar type of form eliminates large deflection and utilises the material to the maximum possible extent.

Another interesting application is the Tension-field Beam. Not much known outside the field of aeronautics, the Tension-field beam is a girder or beam similiar to a steel girder of built up sections with web stiffeners. The main difference is that the webs are of very thin aluminium sheets which are specially permitted to wrinkle or buckle under shear stress caused by the load. The wrinkled webs then start functioning as tension diagonals as in ordinary open-web trusses, thereby creating a "tension-field" within the web. As this was first developed by Wagner in 1929, who also propounded its theory, it is often called the Wagner Beam.

A better known counterpart of the Tension-field beam is a sandwich panel which the flanges rather than the web are made of strong thin sheets of aluminium. The core is made of wood, honeycomb, or pulp-base materials. The main idea of such a composite construction is to place the strong principal structural elements as far apart as possible to obtain a large moment of inertia with the ensuing benefits of increased flexural and torsional rigidity and low overall density. Such designs give extremely light weight panels which can be used for walls and other non-stress-bearing members.

A logical development from aeronautics and one having wide but hitherto unexplored potentialities in structural engineering, is the Space frame, like the triangular and Octet trusses. Generally structures have been designed so far as two-dimensional systems leaving out the considerations of the third dimension with its attendant advantages, purely because of the difficulties of analysis. Aircraft designers have long recognised this aspect and incorporated the three-dimensional concepts in their fuselage and wing structures to effectively carry torsional eccentric loads. In the great circle beam of Britain's Dome of Discovery, a triangular aluminium truss of special sections was adopted on this principle to simplify the work. Many European authorities have carried out work on this subject. Kavanagh of the U.S.A. has shown that a triangular welded steel space frame used as a two-lane deck highway bridge of 120 ft (36·576 m) span (and subjected to AASHO loading for Highway Bridges) would be 21% lighter than a bridge truss of conventional design. If now aluminium alloys are used instead of steel the overall saving in weight over the conventional steel truss would be of the order of 70%.

Methods of fabrication by welding offer certain economics in aluminium design especially when rationally adopted. Care must be taken however about the special nature of the alloys as there is some reduction in strength near the welds.

Suggestions

It is very necessary to expand the nature and overall scope of investigations to enable the light alloys to be used as freely as the other conventional materials in the domain of structural engineering. For this task which is by no means easy, the author suggests the following modus operandi :

(*a*) The first essential requirement is standardisation. Out of the several varieties of alloys a few, such as the Indian Standard alloys HE 10 WP and HE 15WP, suitable for structural applications should be standardised. This would reduce a lot of confusion and the structural engineer would feel more secure and confident of adopting these light alloys instead of searching his way through a maze of alloys of doubtful utility.

(*b*) Once such a standardisation has been made, extensive investigations should be carried out—both analytical and experimental—so that all structural design data can be evolved and perfected on the basis of these selected structural aluminium alloys and concerted ideas established.

(*c*) These concepts would enable the aluminium industry to know the exact requirements of type, forms, and sections needed by the structural engineering workers and enable them to concentrate on production of these forms only instead of attempting to produce a wide range of little practical use. Economic factors would also display themselves very strikingly in this manner.

(*d*) The Indian Standards Institution should issue Codes of Practice for structural aluminium to simplify design procedures. It is understood that this work is included in the ISI's programme and data are being collected at present. Experimental verification would have to be carried out before such codes are finalised.

(*e*) The Institution of Engineers (India), the Indian Institute of Metals, and the Indian Institute of Architects, should each set up committees to go into the question of coordinating the standards and collecting material with the ultimate aim of evolving the necessary by-laws for day to day use.

(*f*) Engineering colleges and especially institutions of higher technology, such as the four institutes at Bombay, Kanpur, Kharagpur and Madras, should introduce specific courses of study in theory, design and practice of aluminium structures. Side by side they should also evolve a programme of experimental research on a systematic basis, which could be coordinated with similar work at the various appropriate National Laboratories.

(*g*) The aluminium industry should pool their resources and set up a development organisation to make both the laymen and engineers more "aluminium-minded". Such associations exist abroad, such as the Aluminium Development Association of U.K., and Centre Technique de l'Aluminium, of France. Reports and bulletins could be regularly issued, seminars could be held, and even scholarships offered at the universities for the furtherance of this objective.

These are some of the salient suggestions, which, in the author's opinion, require to be put into operation as early as possible. The nicrease in the output of aluminium in the Third Five Year Plan, and the general increase in industrialisation will make heavy demands on the materials technology of the nation. One such important and rising material is aluminium which offers wide potentialities to whosoever is prepared to make the use of it thoughtfully and economically.