MOTORCYCLE ENGINEERING—5

THE FRAME

General problems facing the designer in his choice of a stress-bearing structure

By PHIL IRVING

THE frame of a motorcycle has two main functions. It acts as a beam supported by the wheels to carry the weight of the propelling machinery and the rider, and it provides for free steering movement of the front wheel while maintaining the rear wheel continuously and accurately in the centre-plane of the machine.

If the second requirement is not fully met, the rear end will do some uncontrolled steering of its own accord, with adverse effects on the handling. Besides road shocks which (as described in previous articles) have a tendency to deflect the rear wheel and, in effect, to twist it in relation to the frame, very powerful forces may be generated by power-transmission from engine to rear wheel and by braking on either wheel. The frame must be strong enough, both generally and locally at points of major stress, to withstand these forces without undue deflection.

These statements might appear to be self-evident and are certainly well appreciated today, but many years went by in the formative period of the industry before their full import was realized by designers generally, with the result that machines went into production which did not handle well, or suffered from frame breakages in service or, in extreme cases, combined both defects.

Early Designs

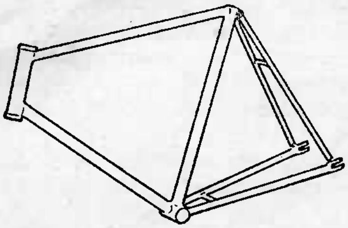
The earliest popular designs were, understandably, merely powered versions of the pedal cycles of the period. The frame of such a machine consisted essentially of a diamond-shaped structure made with steel tubes brazed into lugs, and with a simple front fork mounted in bearings in the tube or lug which formed the steering-head. The engine, while it was still only of small capacity, was clipped or bolted to any part of the frame where a good home could be found for it. In the total absence of clutches or gearboxes and the relative absence of power, pedals were retained and, in fact, were often indispensable to forward progress on hills.

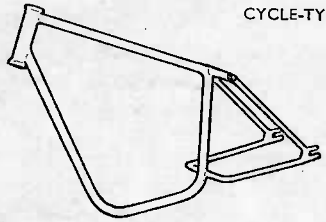
To permit effective operation of the pedals the saddle had to be kept high and the bars had to be at a corresponding level for reasons of comfort, so the whole machine was inclined to be ungainly, especially when engines of larger size came into use and were fitted vertically in the centre of the frame. Nevertheless, this form of motorcycle is still built today under the title of motor-assisted bicycle or, more succinctly, "mo-ped." In principle modern examples differ very little from their ancestors, although, of course, the standard of workmanship and the method used to obtain good performance and a minimum of weight without sacrifice of reliability are vastly improved.

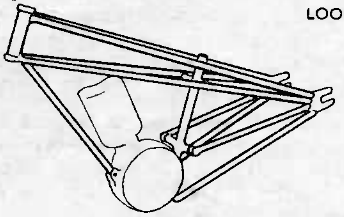
When clutches and variable-speed transmissions made their appearance, the necessity for pedals ceased and with it the need to provide clearance for a pair of revolving feet and enough saddle height to permit freedom of leg-action. This cleared the decks considerably and gave any designer with an unfettered mind the opportunity to devise something original—if perhaps of doubtful merit. Even today, however, traces of pedal-mindedness can be discerned lingering on in some products.

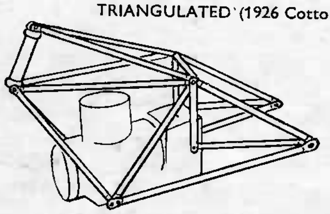
Considered as a beam supported by the rear wheel and the lower bearing of the steering column, the classic cycle-type frame is potentially very strong in relation to its weight, due to its considerable depth in the direction of the major stresses, but unfortunately this advantage could only be exploited fully if the fork had no rake and the steering column was vertically over the point of tyre-contact. In practice, the rearward inclination of the column, provided to give the desired rake, sets up forces in the steering-head which pull the lower bearing forward and push the upper bearing back (Fig. 1), thus tending to bend the top tube and down-tube into the shapes indicated.

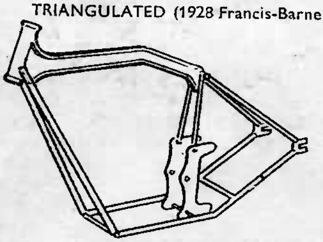
When the model is moving and subjected to road shocks these local forces vary greatly in magnitude and may even reverse in direction under very heavy braking, though, fortunately under most braking conditions the effect of the retarding force is

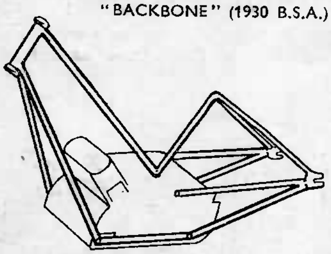

CYCLE-TYPE

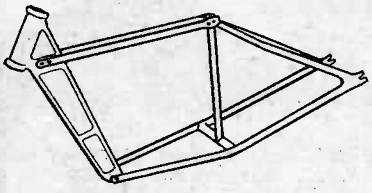

LOOP


TRIANGULATED (1926 Cotton)


TRIANGULATED (1928 Francis-Barnett)


"BACKBONE" (1930 B.S.A.)


SEMI-TRIANGULATED (Early Scott)


"FRONTBONE"

to reduce the local bending action. Nevertheless, as far as the life of the frame structure is concerned, it is the *variation* in stress from a high value to a much lower one which is the most important factor. While almost any component will withstand a steady load nearly as high as the tensile strength of the material for an indefinite period, it will fail sooner or later under a varying or alternating stress unless the maximum value is very much less than the ultimate stress or, more correctly, the yield stress of the material.

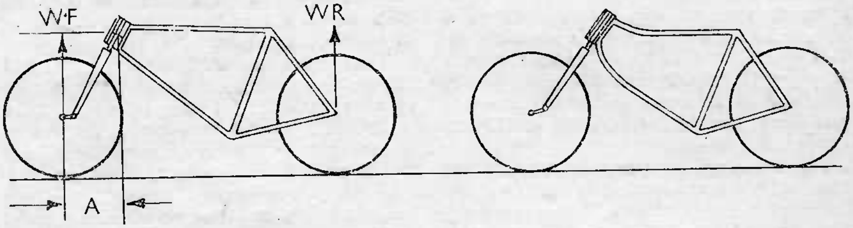


Fig. 1 *Forces acting upon the steering head of a simple cycle-type frame. If the weight supported by the front spindle (WF) is 150 lb. and the horizontal distance from the spindle to the middle of the head stem (A) is 10 in., the bending moment applied to the steering head will be 125 lb./ft. Radial loads of 250 lb. will act forwards on the bottom bearing and backwards on the top one under static conditions. These loads may be multiplied from 3 to 10 times under impact. They tend to distort the frame as shown on the right.*

Fatigue Failure

Failure of this nature is termed "fatigue failure." It is most likely to occur at places where there are concentrations of stress, or where different sorts of stress—i.e., tension plus bending, torsion (twisting) plus bending, or more complex combinations—act on a component simultaneously. Any rapid change in section, such as at the point where a tube leaves a lug, acts as a "stress-raiser," and if the tube is locally reduced in thickness by careless filing up after brazing two bad effects are introduced simultaneously—the stress-raising effect due to change in section is intensified, and there is less metal left to withstand it anyway. (Fig. 2).

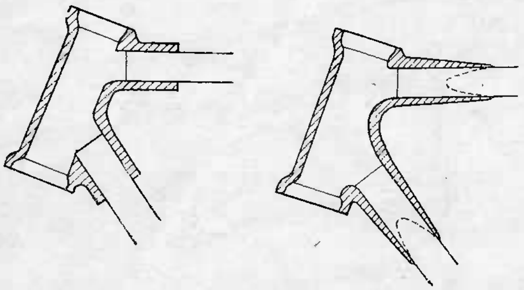


Fig. 2 *Short, thick lugs (left) cause tube failure through stress concentration and lack of flexibility. Long lugs tapered to thin edges transfer stresses gradually for no greater weight. They are better still if fish-tailed.*

The front down-tube is subjected to tension (from the weight of the engine) as well as bending, while the top tube is subjected to compression and bending; but as compression in the normal course of events does not cause fatigue failure, the down-tube is the most likely to fracture and in the old days frequently did so, always with embarrassing and sometimes with fatal consequences.

Stiffening-up

Adding a horizontal tube from the base of the head lug to the saddle down-tube will absorb most of the bending forces, and in fact if both the top tube and this additional tube (sometimes called the tank rail because it was used to carry the tank) are straight and their centre-lines intersect at or close to the saddle lug, the head lug forms one side of a triangle which is extremely rigid in the vertical plane. Even if the tubes are not absolutely straight, but bent to accommodate a tank, the structure is still very stiff, though some makers made the error of joining the tank rail to the down-tube with an additional lug and leaving a short section of tube exposed between it and the head-lug, instead of combining the two. As there was then a tube of relatively small section joining two much more massive lugs, fatigue failure in this area was almost inevitable, especially under the additional lateral bending stresses set up by sidecar work.

Carrying the idea still further, it is quite possible to design the frame in such a way that it is completely triangulated, in which event bolted-up joints are all that is required. Francis-Barnett did produce such a frame in the 'thirties and, as the diagram shows, the triangulation was carried out in the transverse as well as the vertical plane by duplicating all tubes. To be effective all the tubes in such a frame need to be straight as indeed they were, otherwise they will alter in length under the action of end-loading and the value of triangulation will be lost. However, this requirement places serious limitations on the size and shape of the power unit, tanks and so forth which have to be accommodated, and in practice the idea is not so attractive as in theory, though it might well stand resuscitation for the design of a "space-frame" (to employ a car-builders' term) on which full enclosure is to be carried as a standard fitting.

Another fully triangulated design was the Cotton, though in this instance the small-diameter tubes were brazed into lugs in the conventional fashion. The ingenious frame originally designed by A. A. Scott, which is frequently referred to as "fully triangulated," is not so in fact because, seen in side elevation, the head lug, the front down-tubes, the top tube and the crankcase form a four-sided structure in which fore-and-aft head stresses are resisted solely by the strength of the lug and tubes as in a cycle-type frame; otherwise, with engine installed, this frame is triangulated.

Welding Problems

Multi-tubular brazed or welded frames are neither easy nor cheap to manufacture; a lot of machining is required on the lugs and very frequently the frames warp during fabrication and subsequently have to be pulled into alignment by the application of heat and brute force. Also, it is not uncommon to find that there are very severe stresses locked up in the completed structure which are bad in two respects: first, a

High strength/weight ratio of the large-diameter top tube in a racing frame, made for Arthur Wheeler's Guzzi "special" by Reynolds. The tube acts as an oil tank.

permanent high stress is placed in the tubes affected, to which any dynamic loads occurring in service will be added; secondly, the frame when subjected to transverse loads may bend easily in one direction, but be very stiff in the other, according to which way the locked-up stress itself is tending to deform the structure.

These internal stresses arise through one part of the frame, which is heated during fabrication, contracting as it cools, thereby putting itself in tension and some other component in compression. They may be detected if a suspected frame is sawn through at some point. It will often be found that the saw-cut will either open out or close onto the saw, according to whether the tube is in tension or compression: or, if the cut is made in a transverse lug, the two sides may move out of alignment.

Avoiding Pre-stressing

Usually a welding or brazing sequence can be evolved which will obviate such undesirable stressing by ensuring that thermal contractions are equalized, but some makers prefer to have at least one or two joints bolted-up instead of thermally united, so that the final closure does not involve the application of heat. If the holes do come out of line, the adjacent components can easily be set or the bolt-holes reamed so that no residual locked-up stresses are brought into being.

Reverting for a moment to the steering column and top tube assembly: the expedient of staying the head-lug by a tank-rail often involved difficulty with the installation or maintenance of a tall engine, and was undesirable on that account. Furthermore, while a limited amount of fore-and-aft flexibility of the head is not greatly detrimental to handling, twisting of the head out of the centre-plane is most decidedly so, because its effect in moving the tyre contact point off-centre can be considerable due to the distance between the head and the ground.

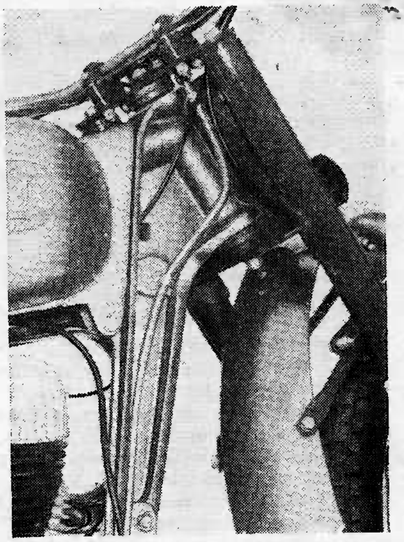
Properties of the Tube

The properties of the tube also affect this issue. While the weight of a thin-walled tube increases almost in direct proportion to its diameter, its torsional strength increases as the *cube* of the diameter and its deflection (for any given twisting moment applied to it) decreases as the *fourth power*. Therefore, a single 2-in. tube weighs the same as two 1-in. tubes, but is four times as strong and will twist through only one-eighth the angle for the same load. Put in another way: a single 1¼-in. tube is almost as strong as two 1-in. tubes, deflects slightly less for the same twisting moment, but is only five-eighths the weight.

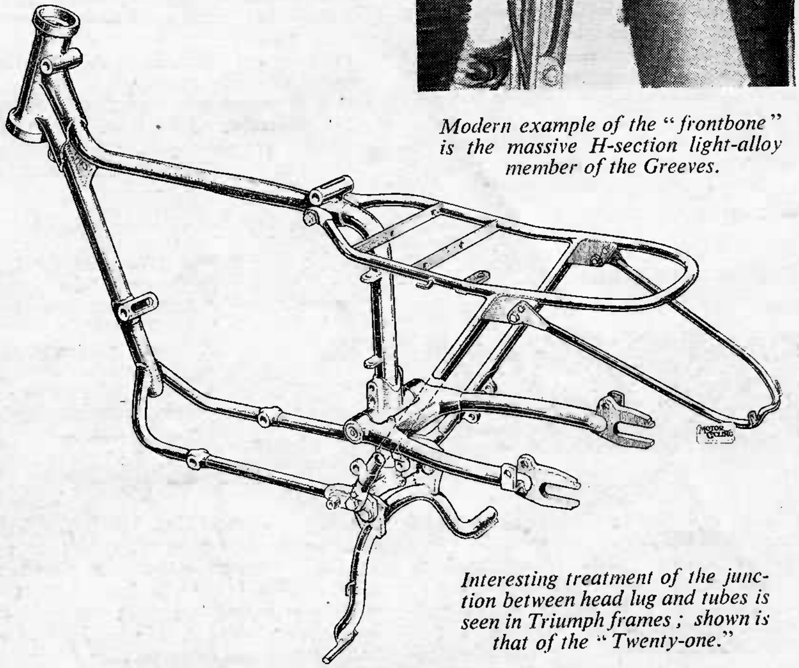
It is, then, clearly more economical in material, machining and labour to use a single tube, taking care of the local head stresses by careful design of the lug or by using a butted tube, which means one that is increased in wall thickness at one end, usually by two gauge sizes. Thus a 12-gauge tube may be butted to 10-gauge for, say, 3 in. at one end, with a tapered portion of 2 or 3 in. to give a smooth change of section. On occasion, double-butted tubes—i.e., with a thicker gauge at both ends—have been employed for top tubes to give a slightly greater margin of strength at the saddle-lug end.

When there are only two tubes attached to the head, another factor, that of the *relative* flexibility of the tubes, must be considered. It was occasionally found that an attempt to eliminate down-tube failure by increasing the gauge of this component was not successful until the thickness had been increased to a disproportionate amount whereas the original thickness was quite satisfactory if the top tube—i.e., the one which was not giving trouble—was stiffened by butting.

This apparent paradox can be explained by envisaging the lug and tubes in a distorted state, as shown in Fig. 1. If the down-tube is increased in thickness, it becomes less flexible than the top tube. It will then attempt to do more than its fair share of the work, and will continue to break until it has been thickened so much that it can do all the work by itself, with the top tube acting more or less as a strut. On the other hand, if the top tube is strengthened it becomes stiffer and consequently takes a greater share of the work, with a corresponding reduction of stress in the down-tube.



Modern example of the "frontbone" is the massive H-section light-alloy member of the Greeves.



Interesting treatment of the junction between head lug and tubes is seen in Triumph frames; shown is that of the "Twenty-one."

It is, of course, quite possible to design the frame in such a manner that almost the whole duty of supporting the head lug is performed by a rigid downward extension, a form of construction introduced by Francis-Barnetts many years ago and still retained by them. Originally the head-lug had an H-section extension (since altered to a lighter and stronger tube) reaching down to crankcase level and maintained in the correct fore-and-aft position by bolted-on duplex tubes on which the tank rested. In the Greeves, a similar structure is used but the main member is a casting of high-strength light alloy with a single top tube running back from the upper end to the saddle; this tube is of steel and is welded to a steel head insert.

A variant of this scheme is to make the head and tank rail integral, and resembling one half of the beam-axle now almost extinct on cars. This method (once used on small P. and M. and Vincent machines) simplifies the tank design; but if the weight is to be kept down the long horizontal portion must be of H-section, which is deficient in torsional stiffness.

An interesting recent development of the idea is found on Triumph frames, in which a single top tube running horizontally just above the engine is curved upwards at the front to fit into the angle between the tube forming the head lug and the front down-tube. Increased resistance to fore-and-aft loads is provided by a single gusset in the space between the top and down tubes, which helps to distribute the bending loads between these two components.

(*To be continued*)