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The Institution of Mechanical Engineers (Railway Division)

Development and structural testing of the Class 87 locomotive bogie frame

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(Advance copy subject to revision)

Paper to be delivered to the Railway Division of The Institution of Mechanical Engineers, 1 Birdcage Walk, London, SW1H 9JJ, on Monday, 20 October 1975 at 1730

Published by Mechanical Engineering Publications Ltd for the Railway Division of The Institution of Mechanical Engineers at 1 Birdcage Walk, London, SW1H 9JJ. (Tel: 01-839 1211)

Development and structural testing of the Class 87 locomotive bogie frame

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May 6, 1974, marked the commencement of British Rail's London to Glasgow electrified services. To operate those services and to augment the existing fleet of Class 81–86 electric locomotives, thirty-five Class 87 locomotives were built in 1973 and 1974. The bogie frame for these locomotives forms the subject of this paper which describes the development and testing of the prototype frame. The paper also refers to such associated subjects as fabrication, finite element analysis and fatigue life prediction.

In this year of British Rail's 150th anniversary celebrations there must be many who wonder why, after so much experience, it is necessary to undertake the sort of exercise described below when a conventional two-axle bogie still consists basically of a frame with a wheel at each corner. The facts are that the design techniques currently available are not sufficiently accurate nor far enough advanced to justify full scale production of a totally new bogie without first confirming the adequacy of its design by testing a prototype. An assessment of the bogie frame design was therefore made a major requirement of the commissioning trials, which also presented the opportunity to demonstrate the integrity of the structure and its ability to withstand the ever increasing demands on utilization without fatigue failure: up to 400 000 km (250 000 miles) per annum in the case of the Class 87 locomotive, and a large proportion of this in the 125–160 km/h (78–100 mile/h) range. The paper also shows that the cost of development and testing was more than offset by the savings on modifications that would have been necessary had the original design been put into production. A more obvious reason for the project was, of course, that it is so much easier to alter a drawing than the locomotive fleet.

Design and manufacture

The fabricated box section of the Class 87 bogie frame design differs from its immediate predecessor on the Class 86 locomotive in a number of important features, shown to be necessary from the technical advances in understanding the environment of railway vehicles and track dynamics. These features include Flexicoil spring secondary suspension and revised helical spring primary suspension; an advanced design of resilient drive from the frame-mounted traction motor to reduce the bogie unsprung mass, in place of the more common axle-hung traction motor; developments in welding technology permitting the frame to be designed to a higher class of weld detail than in the past, and an increase in locomotive continuous power rating from 2685 to 3730 kW (3600 to 5000 hp). It was a policy decision that the basic AL6 locomotive body style and construction should be perpetuated into the AL7 to minimize design and development time, as well as cost. This decision placed many restrictions on the bogie designers, such as the bogie wheelbase and overall length and the space available for the bogie as defined by the body underframe. Perhaps the greatest problem though was to accommodate the 586 mm (23 in) long Flexicoil springs between the body and bogie frame, as space could not be allocated within the body structure. Despite an extensive feasibility study there was no realistic alternative to these springs seating on a platform cantilevered from the underside of the bogie solebar (Fig 1).

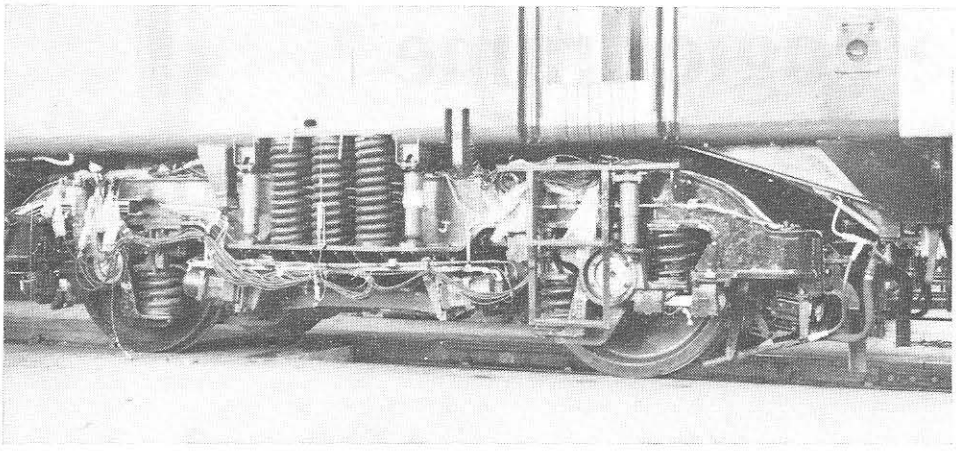

Fig 1. Class 87 bogie instrumented for dynamic tests, showing Flexicoil springs and primary suspension detail

Although the paper is devoted to the structural aspects of the bogie it is considered useful at this point to include a few notes on the suspension system of the Class 87 locomotive. The trend to higher operating speeds, sustained for long periods, together with the necessity to reduce maintenance costs have made it desirable to provide improved forms of locomotive suspension. This applies especially to:

1. Bogie rotational stability, in other words the susceptibility to hunting. In the past, stability was generally achieved by friction between mating surfaces on the bogie and body, the problem being that friction is very unpredictable.
2. Bogie lateral freedom, that is the ability of the bogie to accommodate track irregularities without transmitting them into the body. Most locomotives in fact have restricted movement connections between the bogie and body to transfer traction forces.

Various attempts to overcome the problems raised in meeting these two requirements have been made over the past 50 years, including an extensive development programme within British Rail, culminating in the Flexicoil secondary suspension system. These springs, shown in Fig 1, provide the sole means of supporting the underframe on the bogies and at the same time control transverse and rotary movement between the body and bogie. Traction forces between the body and bogie are transmitted through a body-mounted king pin and metal interleaved rubber traction pads before and after the king pin, between the bogie transoms. These pads have a high resistance to compression but are soft in shear.

The primary suspension can also be seen in Fig 1, comprising twin helical springs between the axlebox and bogie frame. Longitudinal and transverse location of the wheelset, the transmission of traction forces and primary suspension stiffness in both planes are provided by Alsthom rubber-bushed radial links.

Viscous damping for primary and secondary suspensions is provided as necessary.

It is outside the scope of this paper to comment quantitatively on the ride characteristics of the Class 87 locomotive, but the author considers it sufficient to say that the Flexicoil secondary suspension system has been tested satisfactorily

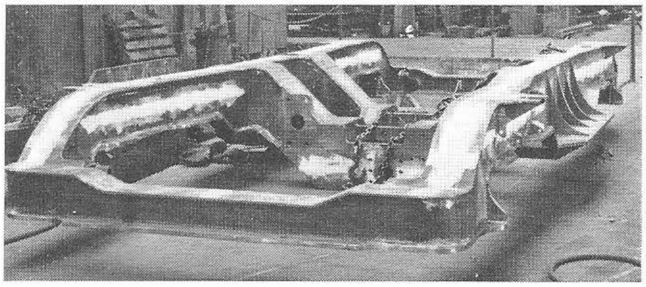

Fig 2. Production version of Class 87 bogie frame

at speeds up to 210 km/h with the Class 87 bogie and up to 229 km/h with the High Speed Train power car.

Within the constraints imposed by the traction motor suspension and locomotive body, conventional design procedures were followed and a ring frame with transoms created, as in Fig 2 (this shows the production design). For calculation of the frame stress levels the static load on the bogie was based on the locomotive weight assessment, whereas the dynamic load inputs were based on the AL7 locomotive traction and braking specification together with the results of service testing on other locomotives, in particular an AL6 locomotive fitted with the prototype Flexicoil suspension.

The bogie frame design was based on rectangular box section members, fabricated with a weld configuration made possible only by relatively recent advances in welding technology. Until 1971 box sections for this type of application were generally fabricated with fillet welds (Fig. 3a) or, in an

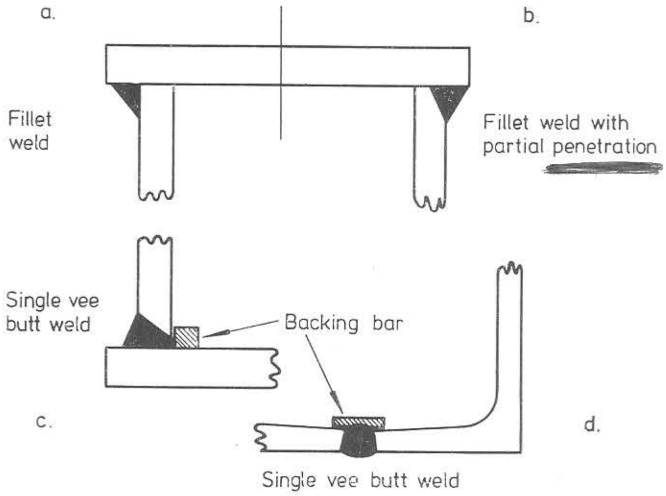

Fig 3. Methods of fabricating box members prior to development of 'inner shield' welding

attempt to obtain improved weld penetration, with a modified fillet weld with partial joint preparation (Fig 3b). These two methods of fabrication produce a joint which is susceptible to fatigue failure from the weld root, especially when the box is under torsional or shear loading. Box members fabricated in this manner also suffer from an inherent weakness of the joint. In an effort to overcome these deficiencies butt welds were produced by means of a permanent backing bar, as shown in Fig 3c. Unfortunately full weld penetration of the joint is not always achieved; often the backing bar and its assembly tack welds are left unfused, creating ideal conditions for fatigue failure initiation. Inspection of welds made in this way is difficult, even with non-destructive testing methods. Where straight box members are required it is occasionally possible to employ standard rolled sections welded toe to toe, as in Fig 3d. This fabrication form may also suffer lack of weld penetration into the backing bar.

The shortcomings of these fabrication methods, some problems with frame fatigue failure on an earlier bogie frame design and the need to produce a bogie frame capable of sustaining higher stress levels without fatigue failure demanded improvements in welding technology. This resulted in the Class 87 bogie frame being produced as a closed box with full weld penetration, as shown in Fig 4a. The technique entails the following operations:

1. 'J' preparation of box webs, with no root gap between web and flange;
2. web/tension flange joint, root passes 1 and 2, MIG (CO_2 shield)/solid wire;
3. web/compression flange joint, root passes 3 and 4 (external access only), MIG (no gas shield)/flux cored wire (inner shield;
4. joint filling passes 5 to 8, MIG (CO_2 shield)/solid wire or semi-automatic submerged arc.

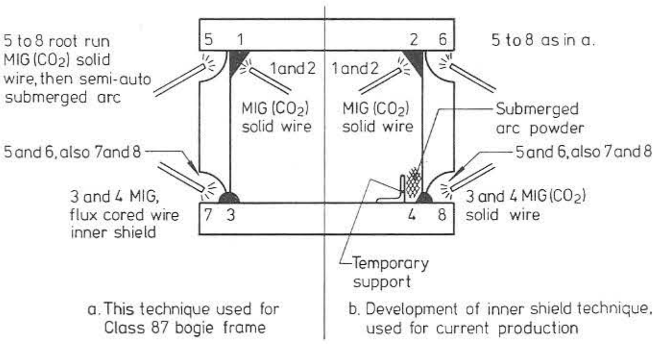

Fig 4. Methods of fabricating bogie frame box members

All welds are made in the downhand position with manipulation as required. This fabrication technique, used also on other bogie and body frames, has proved successful but its main disadvantage is that the inner shield weld is operator-dependent to achieve a satisfactory profile of the inner weld bead (generally convex) at 3 and 4 (Fig 4a). The demands of design engineers for higher standards of fabrication have resulted within the past year in a new welding technique for the closing web/compression flange root run, shown in Fig 4b. Utilizing a commercial idea of flux coated adhesive tape, the space between the temporary support bar and joint is packed with submerged arc powder and the root run passes 3 and 4 are made by MIG (CO_2 shield)/solid wire (external access only). In this way the profile of the root run stop/start positions can be controlled more satisfactorily than is possible with the inner shield technique. The resulting internal concave weld profile can only be described as superb and the technique will be used on the majority of new manufacture of box sections of this type for BR. The technique can be applied to straight and curved box sections. The joint filling passes are completed as shown in Fig 4a.

The Class 87 bogie frame was designed to the permissible stress levels given in the fatigue clause of BS 153, Part 3B, Stresses in Steel Girder Bridges.[1] The fatigue data contained in this specification are applicable to all dynamically loaded, fabricated steel structures—the metal being unaware of its environment—and are used throughout BR. The same fatigue data are given in BS 2573, Permissible Stresses in Crane Structures. Although the general contents of BS 153 are no doubt well known, perhaps it should be explained that this specification classifies each type of weld joint, from A to G in order of decreasing permissible stress, depending on its configuration and the strain field at the weld. The permissible stress level for each joint is given for a specific number of cycles of stress change in terms of stress maximum and minimum, that is, stress range and mean. During development of the inner shield welding technique, fatigue tests were undertaken on six beams representative of bogie frame members. Of 225 × 150 mm (8.8 × 5.9 in) cross section, these were tested to destruction on a four point, sinusoidal loading system to compare their fatigue performance with their weld classification according to BS 153. All the beams failed from weld stop/start positions, but their fatigue lives more than met the C classification for the longitudinal full penetration welds.

Recent research has suggested that some of the fatigue data in BS 153 are too optimistic for certain applications and that the fatigue limit concept in BS 153 is not totally correct, failures having been experienced in components subject to a large number of cycles at stress ranges previously considered below the fatigue limit. It is also considered that the fatigue process in a welded steel structure is independent of stress mean and is dependent on stress range only.

A revision of this specification is now under active consideration[2] and a re-analysis of much of the existing data on

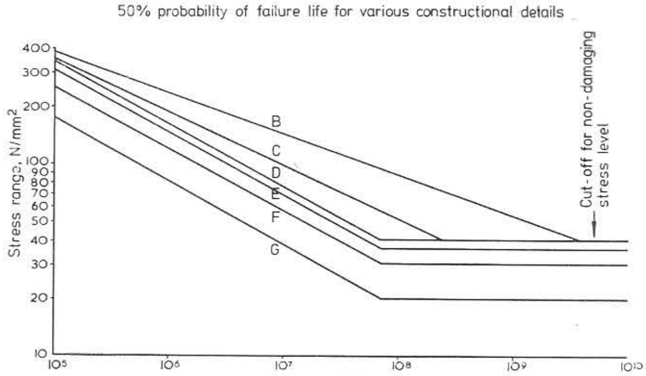

Fig 5. Proposed format of fatigue clause under consideration for inclusion in revision of BS 153

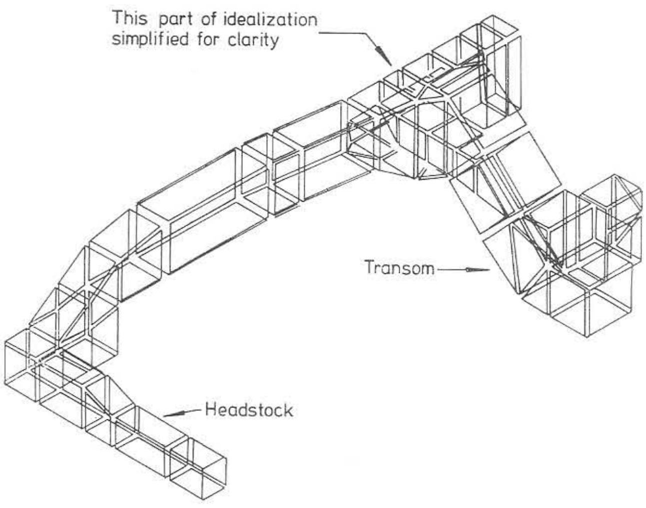

Fig 6. Idealization of one quarter of Class 87 bogie frame

the fatigue strength of welded joints[3] has been made. It is expected that the fatigue data in the revised specification will be presented in the stress range/cyclic graphical style shown in Fig 5. It must be emphasized that Fig 5 is for illustrative purposes only and the data shown should not be used for design or fatigue life prediction. A re-appraisal of the fatigue performance of the test box beams, based on the new data, classifies their weld more conservatively as D. It is unlikely that these changes will have any significant effect on the predicted life of the Class 87 bogie frame.

Finite element stress analysis

Finite element analysis provides a relatively easy computer based method of undertaking theoretical stress analysis of a component subject to a known loading system and permits a much more extensive study than would be normally considered feasible by manual analysis. Finite element methods are being used increasingly throughout BR as a design aid for rolling stock, cranes, bridges and so on. It is thought unnecessary to consider here in detail the analysis applied to the Class 87 bogie frame, for there is adequate literature[4] available for those who wish to know more of the matrix algebra, strain energy and elasto-mechanical theorems which form the basis of finite element methods. The theory is of little consequence to the design engineer whose only requirement is the ability to prepare the input data, analyse the output data and appreciate the limitations of the technique. In this latter aspect it should be understood that the analysis method is only an extension of existing design rules. Although it can be used to determine the overall behaviour of a structure it does not permit detail analysis at stress concentrations, such as welds in a fabricated structure, even with a refined matrix division of the structure geometry. Experience has also shown that the technique is not sufficiently accurate to eliminate service testing, particularly with new components when the exact load input spectrum is unknown.

The computer program developed by BR for finite element analysis is known as Newpac. In addition to stress analysis the program also has the ability to determine the natural frequency of a structure and the effect of mechanical and thermal transients. Associated programs include calculation of section constants, data input checks and graph plotting.

For the Class 87 bogie the analysis was used to estimate the frame stress and deflection distributions when subject to the suspension, traction and braking loads referred to in the previous section, and to provide information for further design study of any identified highly stressed areas. Various different loading conditions on the frame were investigated by Newpac analysis, including 1*g* vertical (that is locomotive static).

A quarter of the frame was analysed and the idealized structure is shown in Fig 6. The main box sections were represented by superimposed membrane and bending plate elements. Areas such as flange overhangs at the primary suspension were represented by end load elements along the box corners. Brackets that were considered to have little effect on the structure stiffness were omitted from the analysis, although it was recognized that certain of these could experience or create local effects, and detail stressing was left to the design engineer. The analysis indicated that the general stress levels in the frame that might be encountered in service were satisfactory relative to BS 153, confirming the initial design calculations.

The Newpac output also included a computer drawn graph plot of the deformation, under load, of the Flexicoil spring platform. The deflected shape suggested that unacceptable stress levels might occur at the upper tips of triangular ribs between the spring platform and outer web of the sideframe. The ribs, sited at either side of each Flexicoil spring, extended to one third the height of the web and were featured in the original design (weld class F, BS 153). Had these ribs been omitted the likely fatigue failure position would have been transferred to the weld between the spring platform (tension flange of sideframe box member) and web. This full penetration weld, produced in the manner described earlier, although in a bi-axial stress field principally sustains a transverse load and could not be classified higher than E, BS 153. While the latter design alternative was likely to have the longer fatigue life, it was still a borderline case and a decision on the production form of the geometry of this part of the structure had to be left until the results of the frame tests were known.

The static tests described later will show that the designed transom/side frame connection was not satisfactory, but unfortunately this was not identified in the finite element analysis. The error occurred because the structural effect of the inner brake hanger was not fully appreciated and it was one of the brackets omitted in the analysis. The behaviour of this part of the frame under load is discussed later.

Static tests

The static tests were essentially an extensive stress survey of the bogie frame while it was subject to the static application of load inputs representative of service conditions. It proved to be the most useful part of the entire development programme, in that it saved many thousand of pounds and days on work which would have been lost in subsequent modifications had bogie frames been produced to the original design.

Strain levels in the bogie frame were measured by electric resistance, foil type strain gauges at specific locations. From the finite element stress analysis and design calculations

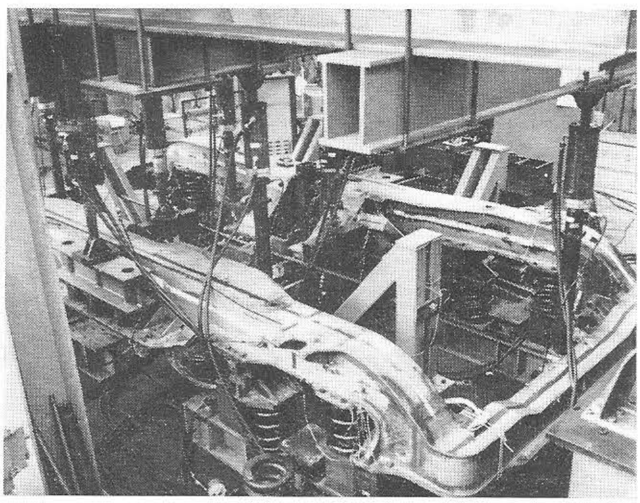

Fig 7. Prototype bogie frame in static test rig, showing reaction brackets and jacks to simulate load inputs

various strain gauge positions were selected to measure the general frame stress. A subsequent visual examination of the frame was made by engineers experienced in structural testing. This resulted in the selection of additional strain gauge positions at features which might be expected to experience high stress relative to their geometry, and thus possibly be susceptible to fatigue failure, such as geometrical changes, plate edges and areas adjacent to low classification weld details. The successful identification of highly stressed features on a structure requires appreciable experience, although some of the uncertainty can be eliminated by the use of brittle lacquer to reveal the stress field at each frame feature. This technique has improved in the past 2–3 years in that the lacquer is less temperature sensitive and easier to use, but it is not capable of indicating low stress levels which themselves may cause fatigue failure of a low classification weld detail.

The tests were carried out with 136 gauge positions, each gauge being positioned along the assumed line of principal stress. In areas of bi-axial load paths, or where the line of principal stress was uncertain, 60° rosette strain gauges were used—though minimized due to their high capital cost. All gauges measuring stress adjacent to welds were positioned with the end of the active portion of the gauge not less than 3 mm (0.125 in) from the toe of the weld. Research into the distribution of stress across a weld has shown that this is the optimum position[5] to measure the weld's nominal stress level. This same location was also used for stress level measurements taken during tests for the preparation of fatigue data. Each of the 136 active strain gauges (6 mm (0.25 in) gauge length) was connected in half bridge formation and the outputs were scanned by a data logging system. Compensation strain gauges, mounted on stress-free steel blocks, were thermally coupled to the bogie frame to minimize signal drift. Calibration was achieved by shunting the active gauge with a resistor, thus creating a known electrical imbalance equivalent to a specific strain. The data logging system with its own computer processed the strain gauge output to produce a stress magnitude at each gauge position. It also had a 'stress level alarm' device as part of the continuous scanning system and automatically completed rosette resolution calculations. The frame areas examined in detail in the stress survey were primary and secondary suspension inputs, brake gear, traction motor and transmission brackets, bogie centre pivot location and transom/side frame connection.

The bogie frame was set up in a test rig inder the portal frames of the MAN large scale test plant of the BR Research and Development Division (Fig 7). The vertical force inputs to the frame representing suspension, traction motor and brake loads were supplied by hydraulic jacks up to 250 kN (25 tonf) capacity and reacted from the portal frames.

Longitudinal traction, braking and transverse curving forces were supplied by hollow ram jacks up to 1 000 kN (100 tonf) capacity, reacted against frames fixed to the test plant floor. The reactions of all loads in the frame were taken through the primary suspension. The load inputs and reactions of the frame are shown in Fig 8.

The static tests on the bogie frame comprised a series of incrementally applied loads, the output of all the strain gauges being recorded and stress calculated by the data logging system at each load increment. The Class 87 locomotive traction forces are greater than its braking capacity and this formed the basis of the four loading tests outlined below. These load cases were also used for the frame design calculations and finite element stress analysis.

1. *Static*, equivalent to locomotive stationary at normal operating weight (83.3 t), to provide mean stress levels for fatigue life assessment in association with service trials. Also for comparison with 1*g* load case of Newpac finite element analysis. Based on locomotive weight assessment during design.
2. *Dynamic* (under power), an assumed condition representative of normal service loading of the bogie frame to attempt

to identify areas of possible fatigue failure. Based on riding tests of locomotive with prototype Flexicoil suspension.

3. *High speed proof load* (under power), the maximum dynamic force inputs likely to be encountered in normal service, but of very rare occurrence. Based on research by R & D Division, Vehicle Dynamics Group.
4. *Crash case*, to ensure that no permanent deformation of the frame occurs in specific crash conditions of $3g$ deceleration of bogie mass—equivalent to a severe shunt.

The effect of reactions to the tread brake (the locomotive normally uses its rheostatic brake) were examined separately. A summary of some of the forces (not all maxima) applied to the frame (not necessarily all at the same instant) during the tests is given in Table 1, as being representative of service conditions.

Table 1. Summary of loads applied to bogie frame during static tests.

Location*	Load	kN
A_1–A_6	Flexicoil spring (static)	42.7
	Flexicoil spring (dynamic)	54.0
B_1–B_4	Transom motor support (motor weight)	12.0
	Transom motor support (motor torque)	±16.5
C_1, C_2	Headstock motor support (motor weight)	9.1
	Headstock motor support (motor torque)	± 6.1
D_1, D_2	Gearcase bracket (static)	4.2
	Gearcase bracket (transmission reaction)	±62.4
E, F	Longitudinal load on traction pads (static precompression)	89.7
	Longitudinal load on traction pads (tractive effort plus precompression)	E/154.2 F/25.2
G	Vertical reaction of primary springs	
H	Transverse body deceleration ($0.07g$)	16.1
J	Transverse reaction at Alsthom link brackets	
K	Longitudinal load in Alsthom links due to tractive effort	16.0
L	Reaction to brake force (tread brake hanger)	±12.7
	Damper loads (not applied in static tests)	
M	Primary (axlebox to bogie frame, 4 off)	10.4
N	Secondary (bogie frame to body, 4 off)	2.4 (some locos 5.5)
O	Transverse (body frame to body, 2 off)	3.0
P	Yaw (bogie rotation, when fitted, bogie frame to body, 2 off)	14.0

*See Fig. 8 for location of load inputs and reactions

The bogie frame was manufactured from BS 4360 Grade 43A steel of minimum yield 247 N/mm² (16 tonf/in²) and to avoid the possibility of permanent frame deformation the test upper limit stress was initially set at 200 N/mm² (12.9 tonf/in²) for tests 1 to 4. The objectives of tests 1 and 4 are stated above and are self-explanatory. Tests 2 and 3 were to investigate the possibility of fatigue failure in service and so the measured stress at each strain gauge position in these tests was compared with the relevant fatigue data in BS 153. The cyclic change in stress level from the static mean on a bogie frame varies appreciably in service and is dependent on the locomotive suspension characteristics, speed, track features and condition. As the Class 87 bogie had, at that time, not been tested in service a dynamic stress or riding spectrum was not available.

However, stress data measured on the prototype locomotive with Flexicoil suspension indicated that a ± 25% dynamic augmentation of the frame static stress level could be expected as a typical stress range occurring in service, and that this range would be representative of the upper limit of the service stress range spectrum. This enabled the stress cycle ratio f_{min} to f_{max} (that is stress mean —25%)/(stress range +25%)) of 0.6 to be obtained. From the BS 153 fatigue clause the maximum permissible stress of each detail investigated on the frame (in other words, at each strain gauge position), at a

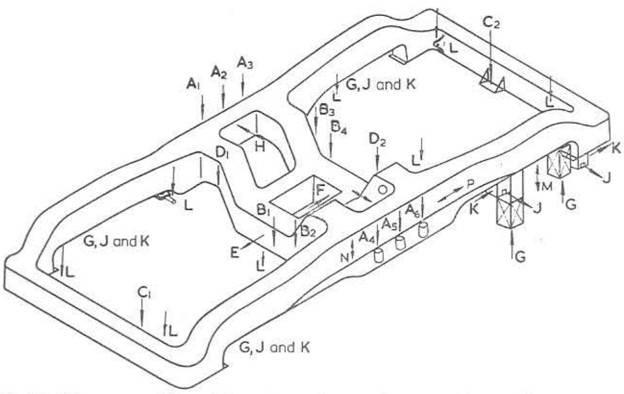

Fig 8. Diagram of load inputs and reactions on bogie frame

stress cycle ratio of 0.6 and relative to its weld classification, could be determined. Thus, comparing this value with test 2 and 3 results, it was possible to assess the susceptibility of each part of the frame to fatigue failure. Included in this assessment was a safety margin to make allowance for the ±25% dynamic augmentation being exceeded on the bogie frame in service.

Two areas of the frame experienced stress levels in the tests of such a magnitude that further investigation was necessary, but with these exceptions the frame design appeared satisfactory on the basis of the static tests. The stress levels, expressed as N/mm², did not exceed the following:

	Plain material	Class F welds
Static test	50	50
Dynamic test	117	40
High speed proof load	130	50
Crash case	180, except minor areas on transom where higher stress was encountered on plate edges as transom 'lozenged'.	

The two unacceptable areas of the frame design were as follows:

1. Secondary suspension platform. The static load tests 2 and 3 demonstrated that neither of the original design alternatives referred to in the finite element stress analysis was satisfactory, the platform requiring additional support to reduce the stress levels. Following tests on various structural modifications, the best solution was determined as extending the ribs to the full depth of the sideframe outer web between the Flexicoil spring positions, as can be seen in Fig 2. The rib edge profile was investigated to determine the shape that would give the optimum stress distribution, within the constraint imposed by the Flexicoil spring deflections. Low stress at the welds at the ends of the rib was achieved at the expense of relatively high mean stress over the centre portion, but this has negligible stress concentration and presented no fatigue problem.
2. The fabricated inner brake hanger. This was welded in the corner formed by the webs of the transom/side frame connection and top and bottom flanges, as shown in Fig 9. The hanger acted as a load carrying tie across the frame corner. High stress was measured on the side frame web and flanges, and on the transom lower flange, algebraically comprising the following:

(a) bending stress due to vertical body loads in side frame reacted at primary suspension;
(b) longitudinal traction forces passing from transom to side frame;
(c) torsion of the transom under the action of gearcase torque reaction forces (see bracket in Fig 9, RHS) and traction motor inner suspension attached to transom;
(d) transverse loads in side frame due to curving forces;
(e) the braking forces in the tread brake hanger received secondary consideration in this instance, as the stress

levels created were lower than those from the effects of traction. The majority of locomotive braking in service is rheostatic, the retarding force generated by the traction motor producing torque reactions as in (c).

In service the fatigue life of this area of the frame would have been a few thousand miles. A solution was achieved by re-replacing the hanger with a casting bolted to the side frame, reprofiling the flanges as in Fig 10 and reducing the gearbox reaction bracket length (and thus the torsional moment on the transom) by 50%. To date this feature has been entirely satisfactory.

Perspex model

Though the static tests had indicated that a satisfactory solution to the design problem of the secondary suspension platform was attainable, it was not practicable to undertake further development on the prototype frame while it was in the test rig. Further investigation by use of a model was considered the most satisfactory solution.

The use of scale models to examine structural problems is well established and a number of different materials may be used depending on the application. For this particular model Perspex was selected, as it is easily worked and thus permits rapid construction, and it has a constant stress/strain relationship similar to that of steel provided a stress level of 5 N/mm^2 (725 lbf/in^2) in Perspex is not exceeded (limit of proportionality). Youngs modulus of elasticity for Perspex is 3.4×10^3 N/mm^2 (220 tonf/in^2), compared with 2.07×10^5 N/mm^2 (13 400 tonf/in^2) for mild steel. Perspex also allows 'cut and try' at low cost and may often present a satisfactory method of achieving the solution to a problem. The linear behaviour of Perspex under load, in conditions of constant temperature and humidity, permits the use of recognized conversion formulae to predict strain at a specific location on a full size structure from load and strain measurements on the model.

A quarter scale model of the bogie side frame in the vicinity of the secondary suspension platform was constructed to the original design. This is illustrated in Fig 11 but in fact shows the final recommended design for the secondary suspension platform. The model is shown coated with brittle lacquer. A rig and loading system were devised for the model, which was supported at the axle centres and transom. A temperature compensating loading ring was used to apply representative body weight to the model at the Flexicoil spring seats. Strain in the model was measured by miniature strain gauges at positions identical to those chosen on the prototype frame. The strain was measured by the same data logging equipment as that used for the full scale tests and the computer program

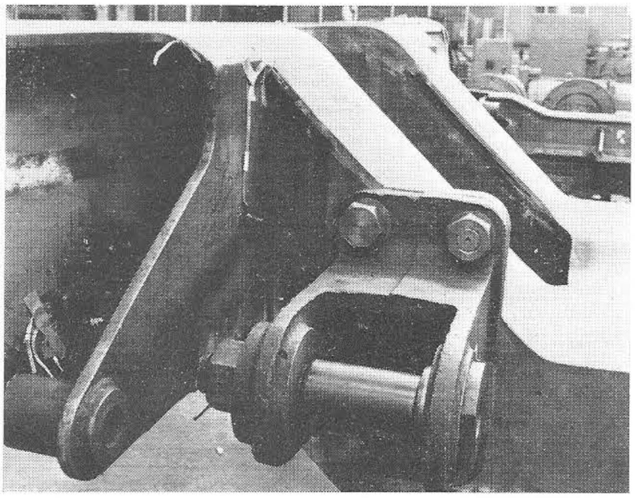

Fig 9. Original side frame (LHS)/transom (RHS) connection, showing fabricated brake hanger (LHS) and gearcase bracket (RHS)

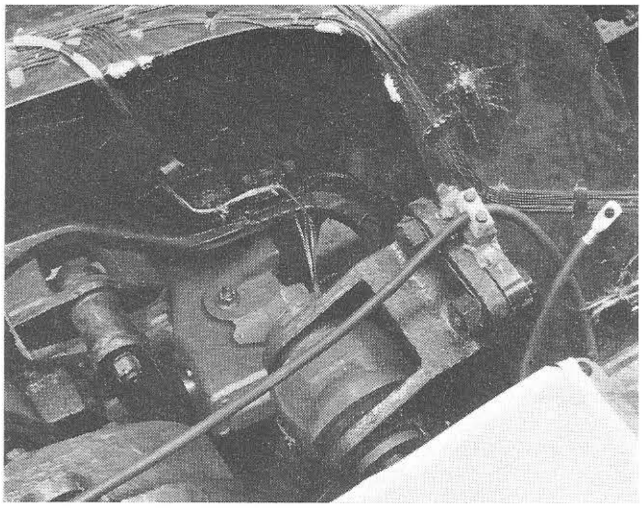

Fig 10. Modified side frame connection, revised brake hanger (LHS) and gearcase bracket (RHS)

included the conversion formulae so that the results printout was of predicted prototype frame stress.

The Perspex sheet used for model construction was between 2 and 6 mm (0.078–0.236 in) thick and some concern was expressed over the possibility of errors being introduced into the results, by the strain gauges causing local stiffening of the thinner Perspex sheets and thus giving erroneous strain measurements. Strain gauges from different manufacturers and of varying characteristics were investigated. Comparative tests on strain gauged Perspex specimens in tension and bending, with measurements made optically, demonstrated that the gauges finally selected for the model had no significant local stiffening effect. The model had a gauge length of 0.75 mm (0.029 in), compared with 6 mm (0.236 in) on the prototype frame.

A series of load/strain tests was undertaken on the model, initially as built and then with modifications, using the prototype strain measurements as a datum. Strain measurements made on the model, while it was in the form of the original prototype frame, were compared first with those at identical positions on the prototype frame under the same loading condition. This was to ensure that the behaviour of the model under load was identical to that of the prototype and that the same strain distribution existed on the model as on the prototype. Once this correlation had been completed, the model strain measurements for the original frame design were considered as a datum. The effectiveness of subsequent structural modifications to the model was assessed by comparing with the datum the strain measurements on the modified model. The objective was to attain the most suitable structural arrangement in terms of fatigue life and cost within the existing design constraints. The outcome was a recommendation to replace the existing small ribs by four large upper ribs between the platform and the side frame outer web, as already shown in Fig 2, and to rearrange the lower ribs (reduced in number from six to four) to improve load transfer from the spring platform into the transom as shown on the model in Fig 11. A brittle lacquer examination of the model in its final form was also made to ensure that no other highly stressed areas had been overlooked.

A model of this type is relatively cheap to create and, as will be appreciated, is an extremely useful development tool. Nevertheless there are justifiable arguments for and against the point at which a model should be employed in this type of project. Experience with this and other models has shown that regardless of the scale accuracy of a model it cannot be relied upon to produce stress levels identical to those on the full size structure. In a marginal case this obviously presents problems in terms of fatigue life assessment. A model can best be used to examine the overall behaviour of a structure and

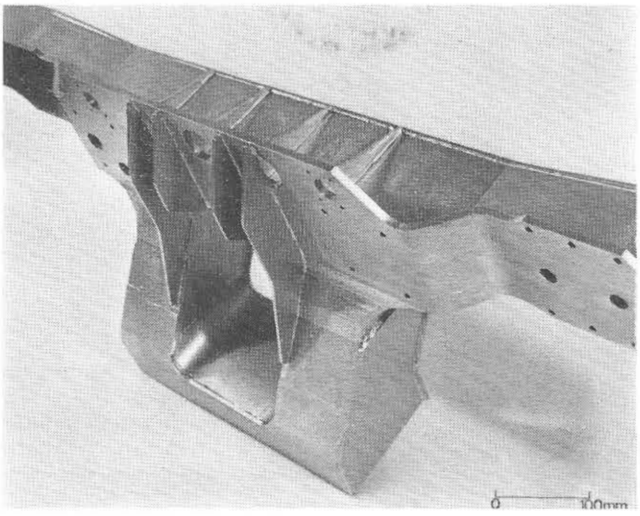

Fig 11. Perspex model of part of bogie frame, coated with brittle lacquer, shows recommended design

to determine qualitatively the apparent best solution. The final decision in such a case has to be based on prototype in-service measurements.

Dynamic tests

The proposed frame design improvements following the static and Perspex model tests were incorporated into the prototype frame in readiness for dynamic tests, with confidence that no further major problems would be encountered. Although much theoretical and practical work has been undertaken towards a better understanding of vehicle/track interaction, it is not yet possible to totally predict the riding characteristics of a vehicle and thus the load inputs from the track reaction. Therefore it was essential that strain measurements were made on the bogie frame in service conditions, to confirm that the stress levels attained during load cases 2 and 3 of the static tests would not be exceeded and to obtain data for a fatigue life estimate for the frame. The dynamic tests were made in conjunction with riding, traction and braking commissioning tests undertaken by the Testing and Performance Section.

The numerous strain gauge positions of the static tests were reduced in number by analysing the test results and eliminating all those positions at which it was considered there was no likelihood of fatigue failure. This analysis indicated that it was necessary to assess only eight features of the frame design in the dynamic tests, though this did not infer that all the areas were thought susceptible to fatigue failure. The areas included traction motor outer suspension, ribs at primary suspension, transom/solebar connection and Flexicoil spring platform. The opportunity was also taken to measure stress on the traction motor tail arm (see Fig 12) and the three motor suspension bolts. Each bolt had a waisted section machined in the shank to accommodate strain gauges and the leads were taken through a hole drilled in the bolt head. The strain gauge configuration was similar to that used for load cells. Each bolt was load/strain calibrated and the instrumentation also permitted each channel to be recorded separately.

The instrumentation available for recording dynamic signals from strain gauges and transducers has improved appreciably in recent years and the process is now much more accurate and automated than ever before. Each active strain gauge, with its compensation gauge mounted alongside on stress-free steel blocks, was connected in half bridge formation. Throughout the dynamic tests the strain gauge outputs were recorded unfiltered through amplifiers and signal conditioning equipment on to magnetic tape. Up to 13 channels of data were recorded simultaneously, together with a control track and voice commentary. A control system has been developed for the tape recorder to record automatically on to magnetic tape an identifying run number and five calibration levels for each data channel, before switching to 'Record' at the start of each test run. The run number and calibration enable the analysing equipment to identify each test and establish reference conditions in the computer. The calibration has multiple levels to permit selection of optimum signal strength and avoid equipment malfunctions. The current of the traction motor with strain-gauged suspension bolts was also measured and recorded during certain tests via a current shunt circuit. The motor current record assisted analysis by identifying periods of acceleration, overload, wheelslip, coasting and braking.

The output of the strain gauges was recorded over all types of track features during the following test series designed to represent service conditions.

Stafford–Crewe: Locomotives and test cars. Constant speed runs over specific test sites including switches, crossings and cwr, at speeds between 48 and 175 km/h (30–110 mile/h). Full service brake tests.

Crewe–Euston: Locomotive, test cars and 15 Mk IID coaches at passenger service timings up to 160 km/h (100 mile/h) maximum on fast line. Simulated freight train service up to 120 km/h (75 mile/h) maximum on slow line.

Whitemore Bank: Locomotive, test cars, twelve 100 t tank wagons and Class 47 locomotive. Starting tests to demand maximum tractive effort from locomotive.

An ultra-violet sensitive paper chart recorder was also used to monitor the tests. The processing of the recorded data and fatigue life prediction are referred to in the following section.

The Class 87 locomotive was projected to have a utilization of between 320 000 and 400 000 km (200 000–250 000 miles) per annum over a 20-year life span. The results of the dynamic tests indicated that the bogie frame could be expected to achieve such a working life without fatigue failure, with the exception of the traction motor outer suspension bracket (see Fig 13). The BS 153 weld classification of the ribs is F, giving an estimated mean life of 5.6×10^6 km (3.5×10^6 miles). This value may be considered adequate but in practice it is difficult to make a satisfactory weld termination at the toe of a rib and the scatter of fatigue life would be appreciable. Although it is recognized that welded ribs are to be avoided in a design there are many instances in which there is no alternative. Unfortunately a rib is often the source of fatigue failure from the weld, due to its low classification and profile. It is thus easy to undermine a basically good design by the unavoidable or careless addition of such an item.

Although further research is thought to be necessary into the fatigue performance of both tension and compression ribs, it is possible to increase their fatigue life by post weld treatment, that is, by profile grinding the weld extremity or termination to remove imperfections, reduce the stress concen-

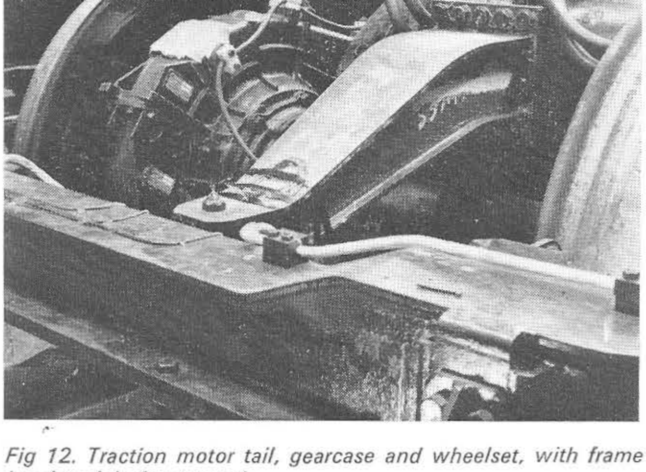

Fig 12. Traction motor tail, gearcase and wheelset, with frame headstock in foreground

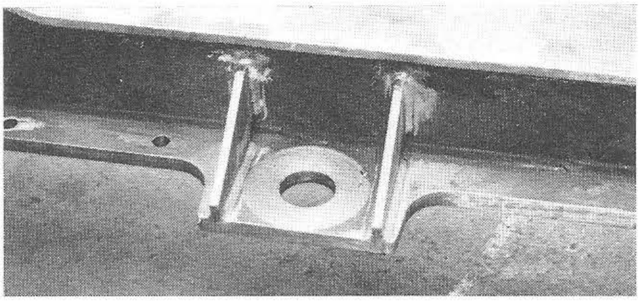

Fig 13. Traction motor outer suspension bracket on headstock

tration effect of the weld toe and improve the load path into the rib. The possible increase in fatigue strength afforded by this technique varies, as shown by a number of workers[5], but a value of +40% is considered realistic and equivalent to raising a low class weld by one grade from, say, F to E, BS 153. Profile grinding was recommended for the traction motor suspension bracket welds and it is estimated that this would increase the fatigue life of the welds by a factor of three. As a precautionary measure profile grinding was also recommended for the weld termination of a number of other similar welded details. The stress measurements did not suggest that fatigue failures were likely but the post weld treatment provided an additional safety margin and facilitated quality control. The modifications to the remainder of the frame, recommended earlier in the paper, proved to be entirely satisfactory and it was concluded that the frame should have a mean fatigue life of approximately 15×10^6 km (9×10^6 miles) based on the planned utilization.

The fully suspended traction motor has many technical advantages over its cheaper axle-hung alternative. However, it presents considerable mounting problems in the bogie frame, necessitating the arm shown in Fig 12, as the AL7 motor/gearbox weighs 4.1 t. The vertical dynamic forces and torque reactions place appreciable stress on the weld of the vertical plate connecting the arm to the traction motor carcase. The dynamic tests indicated that this weld has a mean life of 3.5×10^6 km (2.2×10^6 miles), which is below the design objective. Post weld treatment has been undertaken and the test results show it is reasonable to assume that, if problems do occur with the traction motor tail arm, they will be minor and encountered only towards the end of the working life of the traction motor.

Fatigue life analysis

Many papers have been written on the subject of fatigue and much basic research continues, but the only areas of immediate interest to the design engineer are permissible stress and fatigue life prediction. The determination of the fatigue life of a component under constant amplitude cyclic loading is relatively easy and involves only simple calculations. The problem is considerably different when random cyclic loading is involved, as in a transport application. The solution in such cases can be satisfactorily resolved only by the use of a computer. It is of course possible to manually analyse a random signal, as was done before the advent of computers, but this method is tedious and expensive especially in view of the amount of data analysis necessary for accuracy. Accuracy in fatigue life prediction depends on a number of factors, including careful selection of fatigue data and the recorded strain information upon which the prediction is based. For the Class 87 bogie frame the fatigue data were taken from BS 153. Although a revision of this specification is in progress the author considers that the greatest inaccuracies will continue to occur in classifying a weld detail when one is not dealing with a text book example. It is easy to err on the side of safety by re-assessing a specific feature in a lower class weld, but this is not conducive to the most efficient design of structure. An expansion of the existing weld classification guide is considered essential. This would permit a more consistent classification of welds, whereas at present it is the author's opinion that too much is left to the discretion of the design engineer whose judgement of a particular weld can be appreciably different to that of a colleague.

To further minimize errors in the fatigue life prediction for the Class 87 bogie frame the strain measurements on which the prediction was based had to represent the type of service to which the frame would be subject throughout its working life. This aspect is often difficult to assess for a vehicle as invariably its utilization changes as it becomes older. In many instances the working environment deteriorates as the unit is relegated to secondary lines, though operating speeds tend to reduce also. For this particular bogie frame the problem was somewhat eased in that the Class 87 locomotive, being electric, has a relatively fixed utilization over a specific route.

The Research and Development Division has been responsible for developing BR's computer based techniques for calculating fatigue life from recorded dynamic strain measurements. Programs for two methods of cycle counting are now available and can be used for any type of dynamically loaded structure, only requiring the appropriate fatigue data to be inserted into the program.

The Ranges program based on the BS 153 stress range/stress mean fatigue clause was available for the Class 87 bogie frame. The analogue magnetic tapes of the strain measurements made during the dynamic tests were replayed on to paper chart for visual inspection to ensure that no spurious signals had been recorded. The tapes were then edited to select proportional sections of strain measurements recorded over fast and slow lines at appropriate speeds to represent service conditions. Despite attempts at instrumentation screening, interference is always present in the output from strain gauges used on ac electric locomotives; this is from the 50 Hz power supply. Fortunately the frequency of strain change on a bogie frame rarely exceeds 20 Hz and the 50 Hz or harmonic content of the signal can be removed by electronic filters without significantly affecting the magnitude of the strain signal. A digital analyser scans the analogue signal on the magnetic tape at a predetermined rate based on the signal frequency (typically 10 scans/cycle), transferring it on to a new magnetic tape in binary form. A conversion program in the computer re-records the binary data on the digital tape into real stress magnitudes by comparing the signal with the calibration levels. The Ranges program then undertakes the fatigue life prediction using Miner's linear hypothesis of cumulative damage to calculate the fatigue life from the fatigue damage and the test distance. The computer printout contains the prediction and a matrix summary of the test in terms of the number of occurrences of stress cycles of specific stress mean and stress range. This permits a visual appreciation of the stress/cycle distribution. The results of this analysis were given earlier in the section on dynamic tests.

The other cycle counting method now available is a development subsequent to Ranges, known as Rainflow.[7] Rainflow is a more accurate cycle counting technique than Ranges, due to its ability to count the cycle content of a low frequency signal and a superimposed higher frequency signal, as normally occurs in a transportation environment. The Rainflow program is under continuing development and many fatigue life predictions for which it has been used have employed the stress range only type of data, as illustrated in Fig 5.

There are occasions (as in this instance) when, following the analysis of test results, the design engineer has to prepare and justify modifications. This is sometimes at appreciable cost, incurring manufacturing delays, and often in the face of pressure from production and user functions. It is at this point that the accuracy of the fatigue life prediction is questioned. Since the objective of testing is to avoid structural failure the opportunity to verify fatigue life prediction techniques under service conditions rarely presents itself. The techniques described in this paper were not available when the Class 86 locomotive bogie frame was designed, and between 1969 and 1971 fatigue failures (since satisfactorily rectified) were being experienced in service in the bogie side frames. During that period 100 Class 86 locomotives were affected to varying degrees, the fatigue failures occurring at two specific sites. To assist in determining the most effective repair procedure for the bogie frames a dynamic stress survey, of the two affected areas, was made in service conditions (at that time almost exclusively passenger). Fatigue life predictions were made using the Ranges program and compared with the accumulated service mileage at the time of discovery of each failure. It must be appreciated that the accuracy of the actual frame fatigue life had to be considered objectively, since the frame cracks were in various states of propagation when reported. Nevertheless the computer based fatigue life predictions correlated with the service experience, to the extent that the following conclusions were made. The current methods of fatigue life prediction can be accepted with confidence, providing the user is familiar with the variables that influence the technique. Had the methods of testing and life prediction described in the paper been available at the time, the design of the Class 86 bogie frame would have differed appreciably from the form in which it was originally manufactured.

The strain measurements of each test on the Class 86 bogie were analysed in four approximately equal distance sections, which revealed a wide variation in fatigue damage accumulated by the locomotive travelling at an approximately constant average speed, over a line designed and maintained to a single standard. The fatigue damage summation shown below illustrates this variation and was calculated by the Ranges program from data recorded at a single strain gauge position during one of the test runs.

Section	A	B	C	D
Fatigue damage summation $\times 10^{-6}$	243	156	238	91

A number of factors may be considered to account for this variation but, more important, it illustrates the dangers of making conclusions on the basis of too little test data.

The development and testing described in the paper are necessarily expensive processes since they utilize equipment of high capital cost, have a high labour content of qualified engineers and require the static test rigs to be specially built for each structure. The dynamic tests require the exclusive use of a locomotive out of revenue service for an extended period and invariably complex operating arrangements, sometimes with line possession. The cost of the Class 87 bogie frame project was approximately equal to that of one of the Class 87 locomotive traction motors. Considered in relation to the overall cost of the Class 87 locomotive fleet, or the cost of modifications that would have been necessary had the original bogie design been put into production, the expenditure was easily justified.

Conclusions

Resulting from the development and testing project on the Class 87 bogie frame, it was concluded that with the adoption of the structural improvements the designed working life of the frame would be attainable without fatigue failure. To date the service experience with the bogie frame has been satisfactory and some Class 87 bogies have already undergone their first overhaul.

One of the more important points that the paper has attempted to demonstrate is how quickly design engineers are now making use of new techniques developed by research. Indeed since this bogie was designed there have been appreciable advances in finite element stress analysis and computer aided design techniques. These are now in use. In the past much criticism has been levelled at engineers for not availing themselves of data and new methods evolved by scientists.

It is also concluded that it is essential to improve manufacturing techniques and standards so that they at least keep in step with developments in design. As more and more resources are directed towards perfecting designs, it is necessary to ensure more positively that the end product is as near perfect as the designer intends.

Development work of the type described in the paper has, with variations, also been applied successfully on BR to a wide range of other structures including the HST, APT and Mk III coach bogie frames; Mk III coach, APT and emu coach bodies; tank wagon bodies and a tamping machine frame. If the experience gained to date and the results of continuing research into the phenomenon of fatigue are applied realistically to future designs of dynamically loaded structures, it is reasonable to assume that epidemics of fatigue failure will indeed be of rare occurrence.

Acknowledgments

The author wishes to thank Mr E S Burdon, Locomotive Design Engineer, and colleagues in the following departments of British Rail, Derby, for their assistance in preparing this paper: Research and Development Division, Locomotive Design Office and Testing and Performance Section.

For permission to publish this paper the author wishes to thank Mr G S W Calder, Chief Mechanical & Electrical Engineer, BRB.

The author would like to state that all opinions expressed in the paper are personal and do not necessarily reflect the policy of the British Railways Board.

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