Work is under way in many of these areas, but continued effort will be required to bring about acceptable changes and improvements.

The crosstie fastening system used in North America has remained basically unchanged over many years. The conventional cut spike, steel tie plate, and base-applied rail-anchor system is relatively inexpensive, easy to apply in the field and, until recent years when dynamic loads, speeds, and axle loads increased significantly, has given satisfactory service. To keep pace with change, tie plates have become longer, heavier, and wider. The spiking practice has been changed by increasing the size of the spikes and the number used, and recently, plate hold-down spikes having a more positive locking feature have been introduced. The number of base rail anchors applied has increased with train lengths, and the generally accepted current practice is for every other tie to be box anchored. Disadvantages of this system are that (a) the base-anchoring system loads individual ties selectively (as opposed to uniform longitudinal loading of all ties) and (b) the spike-held tie plates allow serious mechanical wear in the tie plate seat and spike holes. Its major advantage is that it provides a more flexible system of individual tie loading, which limits pumping action.

The European system of track fastening is much more positive than is the North American system. Heavier plates are used, and these are more or less rigidly anchored to the tie with bolts or lag screws. The rail is anchored through the plate system with a heavy clamping or spring force, which controls longitudinal movement of the rail and inhibits rail overturn. Rail cant is provided through the tie plate in both fastening systems.

Early limited use of the European system under the North American loads of the time resulted in loss of surface and line, principally because of pumping. Thus, the more flexible fastening system has continued to be used. However, recent problems related to mechanical wear in ties, rail cant, rail overturning, loss of gauge, track movement or buckling, and other problems of lateral, vertical, and longitudinal stability suggest that the system of tie plate, base rail anchor, and cut spike is operating at the upper limits of its ability to withstand current train load forces.

This suggests the following areas for research:

1. The effect of alternative fastening systems on the lateral, vertical, and longitudinal stability of the track system;
2. The engineering and economic aspects of rigid versus flexible fastening systems, including the effect on the ballast section under North American loading conditions;
3. The determination of the optimum rail cant to reduce both rail damage and timber-tie mechanical wear; and
4. The determination of the level of restraint required or desirable to prevent rail overturn and the means to provide such restraint.

While the timber tie and its unique fastening system developed for North American use has served well, changed conditions now indicate that a critical review, involving economic and engineering research, is desirable to determine a direction for the future. This review should include investigation of the economic philosophy of track maintenance to determine whether the North American practice of individual component renewal and adjustment results in a lower life-cycle cost than does the European system of complete rebuilding of the entire track system near the end of its economical service life. It should also include a critical examination of the fastening system to determine whether current and future force levels can be satisfactorily met with the flexible spike, tie plate, and base anchor fastening system or whether the life-cycle costs will be lower if a more positive restraint system, such as is commonly found in British and European practice, is used.

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Track-Structure Analysis: Methodology and Verification

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Track behavior under traffic and environmental conditions can be predicted by using appropriate methods of analysis. Well-developed concepts and procedures in the structural engineering field are used to illustrate methods of track analysis. These procedures are based on assumptions that often require verification by laboratory or field tests. In this paper, some of the approaches to the analysis of track structure and the methods for laboratory and field tests are discussed.

The purpose of a track structure is to support and guide railway vehicles. In performing this function, the track is subjected to repeated loads, which it must withstand to provide a safe and acceptable ride to the passengers and a nondamaging environment for the movement of goods.

To evaluate the performance and safety of a track and to plan for its maintenance, it is necessary to understand its behavior under traffic and environmental conditions. This can be accomplished by using a systematic procedure such as that illustrated in Figure 1, which consists primarily of a method of analysis that uses two sets of input data. These data are

1. Factors external to the track that contribute to its performance and behavior, i.e., (a) rolling stock characteristics, such as axle loads, arrangement of axles, and diameter of wheels; (b) operating conditions, such as volume and type of traffic and operating speed; (c) environmental conditions, such as frost action and tem-

perature changes; and (d) subgrade characteristics, such as soil strength and stability and susceptibility to frost and moisture and

2. Structural details that influence its behavior, i.e., (a) geometry, such as degree of curvature and gradient; (b) components, such as rail profile, type and dimension of crossties, spacing of ties, type of fastenings, and ballast depth and properties; and (c) type, such as continuously welded or jointed rail.

Methods of analysis generally determine the response of a track in terms of structural values such as deflections, strains, stresses, accelerations, and deformations. These values can be compared with appropriate evaluation criteria to predict track performance. Performance is related to the distress of the track or its components that results from overstressing or from long-term changes in track geometry caused by variations in gauge alignment and surface.

METHODS OF ANALYSIS

Well-developed concepts and procedures in the structural engineering field have been used for track analysis (1). Some of the approaches to the analysis of track structure and the methods for determining stresses in track structure components are outlined below.

In normal operations, railroad tracks are subjected to loads from numerous external and internal forces. The external forces are induced by the rolling stock. They include vertical and lateral forces, as well as the longitudinal forces caused by traction and braking and cause longitudinal bending stresses in the track and high contact stresses in the vicinity of the contact area between the wheel and the rail. The internal forces result principally from temperature changes and residual stresses and produce bending and axial stresses in the track.

Rail Stresses

Flexural Stresses

Generally, the wheels of rolling stock exert vertical and lateral forces on the rail. The vertical load is usually eccentric with an eccentrictiy towards the gauge side. The lateral force acts below the top of the rail head. For the analysis of the track structure, these forces can be replaced by a vertical load applied at the center of the rail head, plus a lateral force and a torque, both acting at the center of twist of the rail cross section, as shown in Figure 2.

The deflection and bending moments due to vertical loads can be determined by any of many methods. One of these methods considers the rail as a long beam supported continuously on an elastic foundation, as shown in Figure 3. The rigidity of this system is defined by the track modulus and determined from the vertical deflection of the rail. To simplify the mathematical analysis, assumptions are made regarding the relations among rail deflection, foundation reaction, and track modulus (2). Work by the ASCE-AREA Special Committee on Stresses in Railroad Track (3) has demonstrated the validity of this method for predicting rail deflections and rail bending stresses due to vertical wheel loads.

Another method considers a continuous rail supported on individual elastic supports, as shown in Figure 4. The rigidity of this system is defined by the spring constant of the individual elastic supports. To simplify the mathematical analysis, assumptions are made regarding the relations among rail deflection, foundation reaction, and spring constant (4). By varying the spring constant of the individual supports, the case of a nonuniform track under normal operating and maintenance conditions can be evaluated.

Both the track modulus with respect to the vertical deflection and the spring constant of the individual supports vary with the service life and operation of the track. They depend on the resilience of the track components, including the rail, pad, tie, ballast, and subgrade. A combined track modulus or spring constant can be determined by considering these components as springs arranged in a series, as shown in Figure 5.

In addition to the bending stresses that result from the beam action of the rail, there are secondary bending stresses in the rail head that are due to the bending of the rail head on the web. These stresses can be determined approximately by assuming that the rail head behaves as a beam on an elastic foundation. The modulus of support reaction of this foundation can be estimated from the compression of the rail web (5).

The stresses that are due to vertical bending of the rail consist of the bending stresses that are due to the beam action of the rail and the secondary stresses that are due to the additional bending of the rail head, as shown in Figure 6. The rail head is subjected to compressive stresses, and the rail base is subjected to tensile stresses.

The lateral force and the torque at the center of twist of the rail cross section result in a lateral deflection and a twisting of the rail cross section. The method of solving for these stresses is based on the assumption that the rail is supported on a continuous elastic system that resists both lateral deflection and twisting of the rail. The rigidity of this system is defined by the moduli of the track with respect to twist and lateral deflection. To simplify the mathematical analysis, assumptions can be made regarding the relations among the angle of twist, the lateral deflection, the reactive moments, the shearing forces, and the moduli of the track. The general solution for the lateral deflection and twist of the rail is defined by two simultaneous differential equations that can be solved by using computer techniques (6).

Another method of analysis for the lateral bending of the track assumes that the rail acts as a short beam fixed rigidly at the fastenings (4), although this assumption does not represent actual track conditions. This analysis shows that the lateral force will produce tensile stresses on the field side of both the rail head and the rail base and compressive stresses on the gauge side, as shown in Figure 7.

The moment of twist will produce tensile stresses on the field side of the rail head and the gauge side of the rail base and compressive stresses on the gauge side of the rail head and the field side of the rail base, as shown in Figure 8. By using this analysis, rail deflections and bending stresses, as well as loads transmitted to the ties, can be determined.

Contact Stresses

The rail head is subjected to localized high stresses in the area of load application. These stresses depend on the magnitude of the load and the curvature of the wheel and the rail at the point of contact. Because of service, progressive wear of both rail and wheel occur during their lifetime, which results in a shift in the position of contact between the wheel and the rail and variations in their curvatures.

The solution for contact stresses in the rail head is based on the approach developed by Hertz for the contact of elastic bodies under normal loading (7). According to Hertz, the pressure between two elastic bodies is distributed over an elliptical area of contact in the shape of a semiellipsoid, as shown in Figure 9a. However, theoretical and experimental studies (8) have shown that under heavy axle loads, plastic deformation occurs in the upper layer of the rail head, so that the assumption of elastic bodies in contact is not entirely valid. The pressure distribution over the contact area varies from the Hertzian distribution and tends to be uniform, as shown in Figure 9b. As a first approximation, a uniformly distributed pressure acting on the elliptical area of contact, as shown in Figure 9c, can be assumed for the calculation of stresses in the interior of the rail head.

By following this procedure, the distribution of stresses in the interior of the rail head can be calculated by integrating the principal Boussinesq equations

Figure 1. Approach to track analysis.

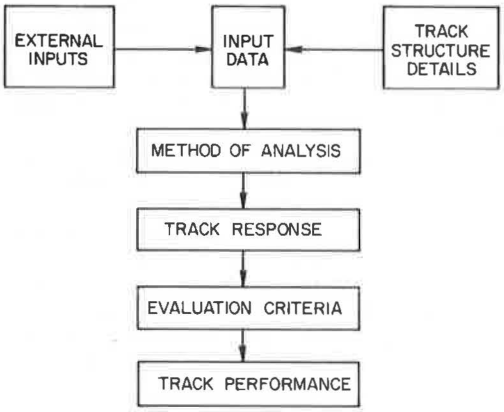


Figure 2. Resolution of forces acting on rail.

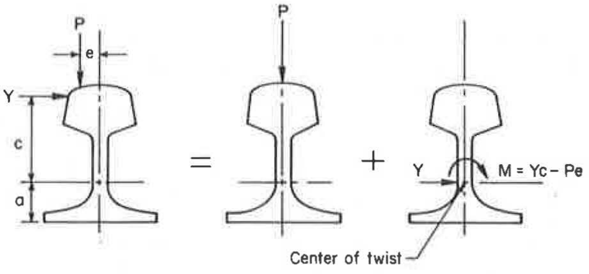


Figure 3. Rail as beam on continuous elastic foundation.

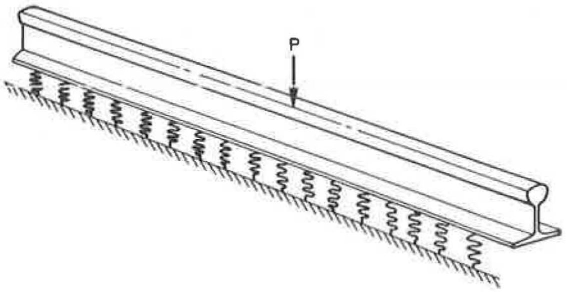


Figure 4. Rail as beam on individual elastic supports.

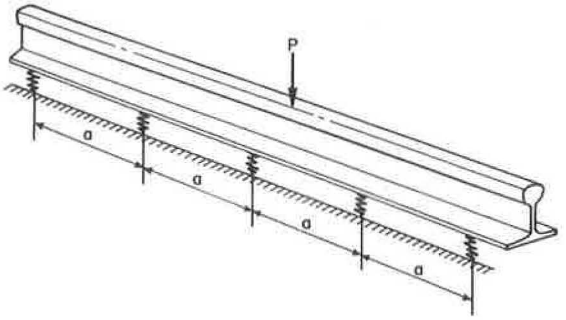


Figure 5. Track as series of springs.

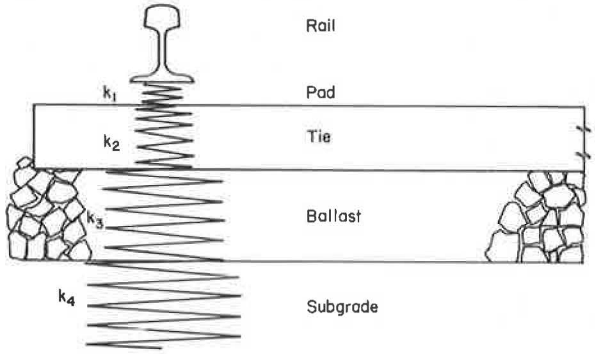


Figure 6. Stress distribution due to vertical bending.

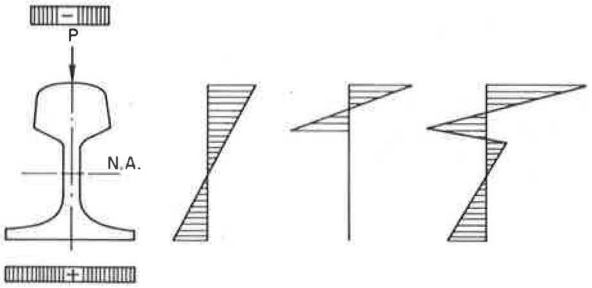


Figure 7. Stress distribution due to lateral bending.

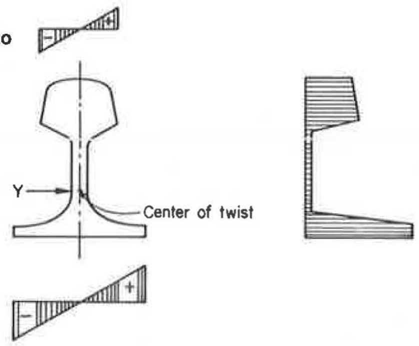
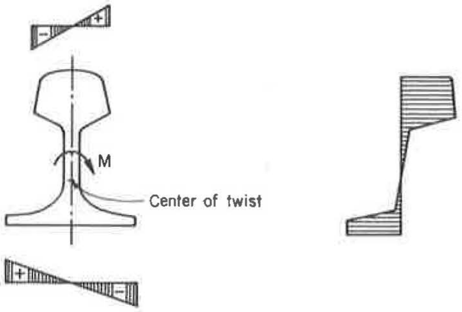


Figure 8. Stress distribution due to twist.



for a single load (9). Experimental studies using model-analogy techniques and photoelastic investigations have verified the validity of this solution (8).

The distribution of stresses in the rail head can also be obtained by using the finite-element method. A three-dimensional finite-element model for the rail head has been used to determine the stresses for a Hertzian pressure distribution (10). This model can also be used to determine the contact stresses due to tangential forces.

By using this analysis, the three-dimensional stress state in the rail head can be determined. To evaluate the effect of this stress state on the material strength, the stresses should be expressed in terms of a single stress designated the significant stress. The significant stress can be determined by using distortion-energy theory (11).

Thermal Stresses

Temperature changes also cause stresses in the rail. For a jointed rail, these stresses depend on the change in temperature from that at which the rail was laid, the length of the rail between two joints, the width of the joint between two rail ends, and the resistance of the joints and of the rail to longitudinal movement. Longitudinal restraint depends on the type of tie plate, the rail fastening, the longitudinal resistance (friction) of the rail on the tie, and the resistance of the tie on the ballast.

As temperature decreases, the rail tends to contract. This movement, however, is restrained by the resistance of the joint bar and the longitudinal rail restraint. The length of rail required to provide full restraint to movement as illustrated in Figure 10 is ℓ. If the rail length between joints is larger than ℓ, the intermediate portion will encounter no movement and will be subjected to the maximum force.

The behavior of a jointed rail laid at a temperature of t_0 is shown in Figure 11.

1. As the temperature decreases below t_0, the rail will tend to contract. In the case of free movement, as the rail contracts, the joint width will increase, and no axial forces will be developed. However, if there are joint and longitudinal restraints, the joint width will remain unchanged, and tensile forces in the rail will develop. After the restraint is overcome, the joint opening will gradually increase, and no additional forces will develop until the temperature reaches its minimum (t_{min}), at which time the joint width will reach its maximum.
2. At the temperature increases above t_{min}, the tensile force in the rail will change to a compressive force to overcome the restraint. At a certain temperature, the joint will close, and any additional increase in temperature will result in an additional compressive force.

For a continuously welded rail or a jointed rail of length longer than ℓ, the potential change in the rail length due to temperature change is restrained by the track resistance. In this case, thermal stress is largest.

Residual Stresses

Residual stresses in the rail originate during the manufacturing process from cooling and straightening and can be determined experimentally. The magnitudes and signs of these stresses depend on the manufacturing process. In general, the distribution of residual stress over the rail cross section is irregular and does not follow a definite pattern.

Residual stresses also originate in the welding process. The amount and distribution of these stresses depend on the welding method.

Basically, there are two methods for measuring the residual stresses in rail. One is to release them by cutting and then measure the strains caused by their release. The other is a photoelastic method that combines the shear difference procedure with the stress-freezing process (12).

Tie Stresses

It is possible to determine the load transfer between track components, particularly rail and tie, by using an established method of analysis. These loads can then be used for the analysis of the tie stresses.

The design and analysis of crossties can be performed by considering the tie as a finite-length beam supported on an elastic foundation. To simplify the mathematical analysis of the problem, assumptions are made regarding the relations among tie deflection, tie and ballast pressure, and modulus of support reaction.

Other methods of tie analysis are based on assumed distribution of tie and ballast pressure that vary with service life and operation of track. Pressure variation can include the support conditions encountered shortly after tamping (Figure 12a), as traffic continues (Figure 12b), and at a full center-bound condition (Figure 12c).

After the support conditions are established, it is possible to determine the maximum bending moments and stresses in the tie. For prestressed concrete ties, the stresses depend not only on tie dimensions, but also on the prestressing force and the location of the prestressing tendons. In the analysis, consideration must be given to the prestress losses that occur during the tie life.

Ballast and Subgrade Stresses

By using an appropriate method of analysis, the pressure on the ballast can be determined. Then, the stress distribution in the ballast and the subgrade can be calculated by using Boussinesq equations for a semi-infinite solid or by using a layered-system analysis (13) similar to that used in pavement analysis. The analysis considers the effects of the subgrade, subballast, and ballast properties; the shape and spacing of the ties; and the depth of ballast and subballast on the stresses in the subgrade.

Dynamic Stresses

The dynamic deflections and stresses of a track under the action of the moving wheels of rolling stock may be much larger than those calculated on the basis of static formulas. There are many factors that contribute to increases in deflection and stress, including

1. Differences in irregularities in the shape of the wheel or rail, such as flat spots on the rim of the wheel, low spots in the rail, and discontinuities at the rail joints;
2. Vibration in the forces acting on the rail caused by variable spring forces on the wheels; and
3. Vibration of the track under moving loads.

Dynamic stresses produced in track by the effect of a low spot in the rail (a corrugated rail profile) or a flattened wheel can be determined analytically (14). For this purpose, the shape of the geometric irregularity can be represented in a mathematical equation. Similarly, the dynamic loads developed near rail joints can be determined analytically. For this purpose, the mathematical model should consider the change in track stiffness at the rail joint.

Dynamic stresses can be accounted for by using an impact factor. Extensive measurements by European railways (15) have shown that the dynamic stresses in railroad track depend on the condition of track and rolling stock and the speed of operation. An appropriate dynamic impact model has been developed to account for the effect of these three factors.

For the analysis of ties, European railroads have used impact factors that reflect the most severe track conditions. A similar approach was followed by the AREA Special Committee on Concrete Ties (16).

EVALUATION

By using the results of these analyses, track deflections and stresses at the critical locations can be determined. The locations of critical stresses are illustrated in Figure 13. Critical stresses include

1. Bending stresses that can result in plastic deformations of the rail head (location a) and the rail base (location b),
2. Bending stresses that can result in fatigue failure of the rail (location c),

Figure 9. Pressure distribution between wheel and rail.

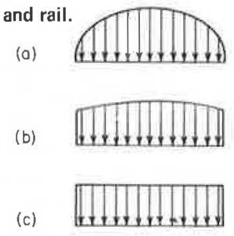


Figure 10. Joint and longitudinal track-restraint forces.

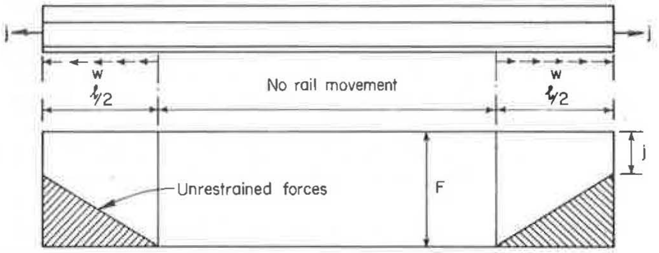


Figure 11. Variation in joint opening and axial force with temperature change.

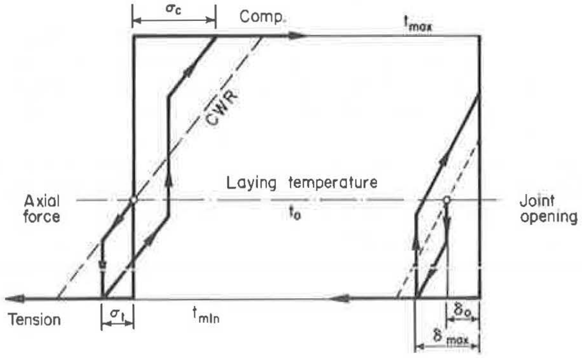


Figure 12. Typical tie-support conditions.

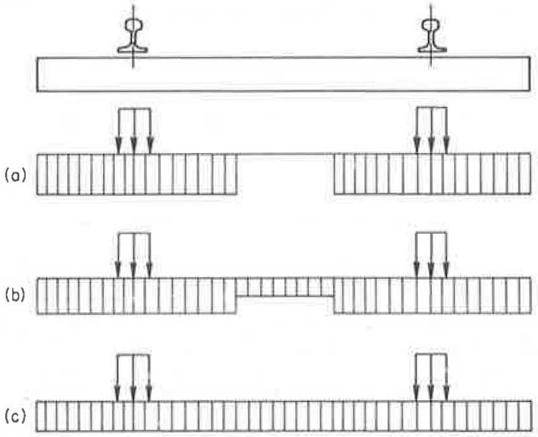


Figure 13. Locations of maximum stresses.

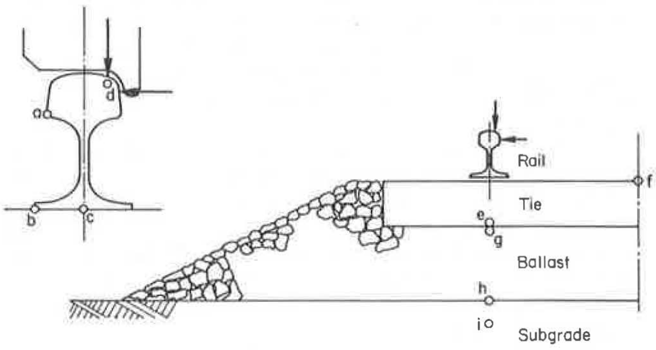


Figure 14. Loading cycle simulating axle and truck spacing.

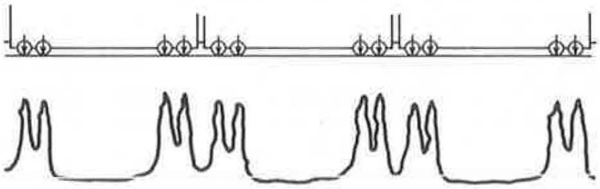


Figure 15. Laboratory tests on tie supported on ballast and subgrade.

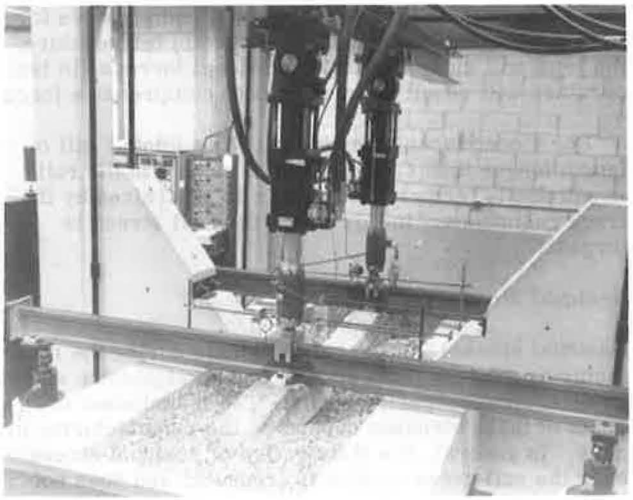
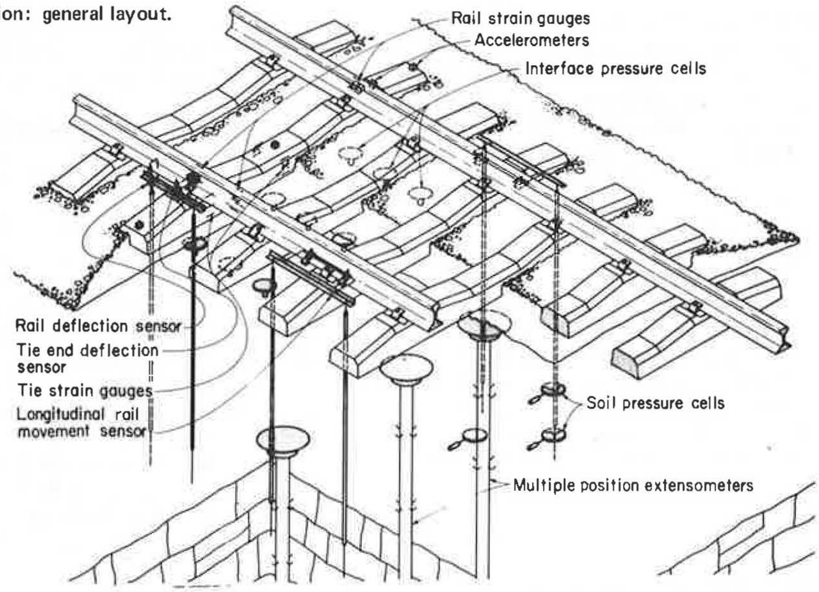


Figure 16. Track instrumentation: general layout.



3. Contact stresses that can result in shelling or fatigue failure of the rail head (location d),
4. Bending stresses that can result in flexural cracking of the crossties under the rail seat (location e) and at the tie center (location f),
5. Pressures that can cause degradation and deformation of the ballast (location g), and
6. Pressures and shear stresses that can result in permanent deformation and shear failure of the subgrade (locations h and i).

Stresses at the critical locations can be used in conjunction with limiting values and theories of failure to forecast the service life and the safety of track components. Thus, remedial actions may be taken at appropriate times.

VERIFICATION

As outlined above, methods of track analysis are complex and based on many assumptions. Therefore, the applicability of the methods and the validity of the assumptions should be verified. This can be accomplished in three different ways:

1. By laboratory testing of track sections or track components,
2. By field investigations of track sections, or
3. By accelerated testing.

Laboratory Tests

In conducting laboratory tests on track systems and components, efforts should be made to simulate the field support condition and the loading environment. This requires a proper selection of track support, loading magnitude and frequency, and pattern of loading cycle. Laboratory tests, when properly designed and conducted, can provide adequate data on the response of a track to traffic loads.

Attempts to provide good simulation should include programming the loading cycles to simulate the effects of axle and truck spacings, as shown in Figure 14, and of speed of operation. Methods of simulating the support of ties and track sections on representative ballast and subgrade have been developed, as shown in Figure 15.

In laboratory tests, appropriate instrumentation can provide quantitative measures of track response. However, laboratory tests can also be designed to provide qualitative information on the performance and properties of track components. In these cases, no instrumentation is provided, and the test elements are examined visually.

Field Tests

In designing a field-test installation, consideration should be given to the site selection. This includes principally the selection of the desired characteristics of speed, traffic volume, track alignment, and environment. Further consideration should be given to the selection of the track structure. A most important consideration in a field-test installation is the design and installation of appropriate instrumentation to measure the required information.

Relatively complete instrumentation of a field-test section, as shown in Figure 16, includes the following:

1. Strain gauges for the measurement of rail and tie strains;
2. Transducers for the measurement of rail and tie displacements, including longitudinal, lateral, and vertical movements of the rail and the tie;
3. Accelerometers for the measurement of rail, tie, and ballast vertical accelerations;
4. Transducers for the measurement of load transfer from the rail to the fastener and to the tie seat;
5. Pressure cells for the measurement of pressure beneath the tie—i.e., at the tie-ballast interface, the ballast-subgrade interface, and various depths; and
6. Vertical and lateral extensometers for the measurement of the soil strains produced by load applications.

A similar array of instruments can also be used for the evaluation of track structure in laboratory tests.

Accelerated Tests

Accelerated tests can be conduced in the laboratory or on a railroad track under accelerated service conditions. An example of a field-test track is the Facility for Accelerated Service Testing at the U.S. Department of Transportation Test Center in Pueblo, Colorado. The test loop has 7.7 km (4.8 miles) of track and consists of 22 test sections. The purpose of the facility is to subject various track components and types of construction to accelerated testing. The track components and types to be tested cover a wide range of variables; these include rail metallurgy, steel, reconstituted, laminated, concrete, and wooden ties, ballast, rubber pads, tie plates, and many others.

In accelerated tests, appropriate instrumentation should be provided to measure the track response. This instrumentation can be similar to that used in ordinary field tests.

The information generated from verification studies, whether conducted in the laboratory, in the field, or in an accelerated service loop, is useful only to the extent that the test corresponds to actual conditions. Therefore, verification studies should be designed and conducted carefully and, of more importance, the data must be interpreted properly.

CONCLUDING REMARKS

A systematic procedure for the analysis of a track structure is described. The procedure uses methods of analysis that are well developed in the structural engineering field. Methods for verifying the analysis by means of laboratory, field, and accelerated tests are presented.

The present standards of track have been evolved from previous practices through a process involving trial, judgment, and experience. This practice has not yet provided a track structure that fulfills its intended purpose. Therefore, railroad track should be developed in a manner similar to that followed in the development of other engineering structures. Analysis and experimentation can contribute significantly to the orderly development and upgrading of our railroad system.

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Track Structure at Facility for Accelerated Service Testing

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An overview of the track structure at the Federal Railroad Administration Facility for Accelerated Service Testing is presented in this paper. The facility consists of a 7.7-km (4.8-mile) loop of relatively conventional railroad track at the U.S. Department of Transportation's Transportation Test Center near Pueblo, Colorado. In September 1976, a loaded freight train began traveling the loop 16 h/d and was scheduled to continue doing so for 1 year, subjecting the track to as much loading as is hauled over an average freight line in 10 years. Many types, makes, sizes, and arrangements of track components (rails, ties, fasteners, and ballast) are used in the 22 track sections of the loop. The rail elements being tested include five types of rails with varying metallurgy or heat treatment, various frogs and guardrails, jointed and continuously welded rail, insulated