to the year 2000, the price index is expected to re­main stable and favorable relative to 1967 prices. But with a decreasing inventory and increasing de­mand for timber after the year 2000, the price index is expected to rise (2).

CONCLUSIONS

In the near future and up to the year 2000, the out­look for timber availability for crossties is favor­able. After 2000, increased demand for hardwood pulpwood, pallets, and miscellaneous hardwood prod­ucts may affect timber availability for crossties, especially in regions where these products compete most for hardwood timber.

The opportunity exists for greater increases in growing stock inventories. This opportunity lies in more intensive, improved forest management. However, such a management level would require larger invest­ments in timber stand improvement, reforestation, and research (9).

REFERENCES


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Steel Ties: A Viable Alternative

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ABSTRACT

Steel crossties are a viable, cost-effect­ive alternative to wood and concrete, but they are not new to the railway industry. Steel ties have been used in Europe since the early 1800s. A recent report indicated that the life of steel ties is much greater than wood ties in the same track under identical conditions. Although the traffic density, matrix, and other conditions in Europe do not apply to the United States, there is no reason that the modern steel crosstie design would not apply in the United States. In addition, an extensive research program was recently conducted to develop and test a range of steel ties, which covered the spectrum of operating re­quirements from iron ore operations to sec­ondary lines. The analyses included ballast depth and tie spacing requirements. All track system components were tested, in­cluding insulating pads and fasteners. Fi­nally, Omark Industries developed a comput­er program to compare costs of different types of ties, including wood, concrete, and steel.

A recent study published by the University of Lau­sanne on the life of steel ties in the Swiss Railway (68 percent steel and 22 percent wood) stated the following conclusions [note that these data are from a collection of research reports on steel sleepers by l’Ecole Polytechnique de l’Universite de Lau­sanne, Lausanne, Switzerland (Number 1, undated)].

The investigation carried out has shown that the steel sleeper has very considerable advantages over the other
types of sleepers for the renewal and maintenance of tracks. Modern means and techniques have been developed which permit this work to be carried out with steel sleepers at least at equal cost, if not more cheaply than with any other type of sleeper. The homogeneous life of steel sleepers considerably facilitates their renewal.

Consequently, steel sleepers maintain a constant life. Wood failures occur intermittently and sporadically. This is an important economic consideration.

Of special importance is that by choosing suitable lighter steel sleeper types with direct fastenings, the purchase price for the sleeper and the fastenings is lower, as a rule, than that of wooden or concrete sleepers.

It must be added that, because of the high scrap value of the spent sleeper, the net investment cost of steel sleepers is considerably lower than that of other types. From this results, for the steel sleeper, lower interest cost and, because of the very long life...considerably lower depreciation costs.

Particularly important is the fact that the economic advantages of the steel sleeper do not depend on specific conditions in individual countries.

The estimated scrap value of steel sleepers is 25 percent of the initial cost.

STEEL TIRES

There are two different types of steel trough-shaped ties: those with uniform wall thickness and those with a shaped cross section comprising a thick top, thin legs, and bulbous edge. The first type is manufactured by pressing a flat plate; the other type is manufactured by either pressing a profiled section or by hot rolling the final shape. The latter method allows better use of materials by varying the thickness of the steel to fit design needs. A cross section of both types is shown in Figure 1. The bottom drawing shows the uniform-wall tie used for light-tonnage railways. The top drawing shows a steel tie with a thicker top to accommodate heavy-tonnage railways.

STEEL TIE DESIGN

The design method consists of three phases:

1. Prevention of fatigue in the fastening area at the rail seat;
2. Prevention of failure in the tie at the base of the rail from exceeded tensile strength, primarily caused by center binding; and
3. Assessment of bearing pressure criteria to ensure that track maintenance costs are controlled.

However, testing is an integral part of each phase in the design of a tie. Testing was performed at the Melbourne Research Laboratory (MRL) in Melbourne, Australia. Testing facilities will be described later in this paper (after a description of tie design phases).

The first phase in the design method involves determining procedures for design that will prevent fatigue in the tie. The procedure for designing a steel tie is given in the following list (the initial aim (number 3) is to establish the section properties of the tie):

1. Compute the permissible maximum stress by using loading history;
2. Establish maximum permissible working stress by considering the tie as a welded beam;
3. Use beam on elastic foundation (BOEF) analysis to establish moment of inertia;
4. Establish cross-sectional shape;
5. Compare results with other ties of known performance; and
6. Finalize rail fastener, mode of cant, and insulation.

(Note that procedures 1-4 require testing or computation or both. These procedures are described in the following paragraphs.)

To compute the permissible maximum stress, failure criteria must be established. Failure criteria in steel ties are usually caused by fatigue (the tendency of material to break under repeated stress). The number of fatigue cycles the tie must withstand equals the number of passing axles expected over the design life, which is usually 40 years. In assessing the cumulative fatigue damage of the tie (1), the loading history must be considered because the load range exerted by the passing axles depends on the spacing of the axles, bogies, and ties.

The number of damaging fatigue cycles is used to establish the maximum range of stress that is permitted at the detail that attaches the fastener. Figure 2 shows a typical load spectrum. Note that one-quarter of the fatigue cycles are at maximum load range, one-quarter are at half-load range, and one-half are at quarter-load range. (The range of load is fatigue damaging, not the absolute value.)

The tie may be analyzed as a BOEF. The theory for BOEF analysis has been thoroughly documented by Hetenyi (2). This analysis is used to calculate moment of inertia in a tie section. The equation for computing the bending moment in a beam with two symmetrically placed loads is documented by Hetenyi (2). Cross-section shape is established by using the moment of inertia determined in the BOEF analysis. The following requirements must be considered when determining the shape:

1. Mass (cost should be minimized but consistent with strength);
2. Width should be maximized to reduce ballast pressure and consequent degradation and track deformation (3), and
3. Height should not exceed a level that would impede tamping of the tie.
The second phase in the design method involves prevention of failure from exceeded tensile strength, which is usually caused by center binding. Several design procedures are available for prevention of center binding, a condition that can cause distortion of the tie. One method—the uniform pressure method—uses the BOREP analysis. In addition, the effect of center binding can be calculated by assuming that, under such conditions, the tie is supported and cantilevered. Consequently, trough-shaped ties should be less susceptible to center binding than flat-bottomed ties, such as wood or concrete, because the central portion of the trough is left unpacked during tamping.

By the nature of their design, trough ties should circumvent center binding unless considerable subsidence into the ballast occurs. Furthermore, trough-shaped ties should require less tamping and maintenance than other ties. Figure 3 shows ballast support under ties. The top diagram shows a flat-bottomed tie and the bottom diagram shows a trough-shaped tie with a gap in the middle where center binding might occur in the flat tie.

The third phase in the design method involves ballast depth and bearing pressure. For a specified shoulder width, the following major factors affect the volume of ballast (track level): tie type and ballast depth. Ballast depths are usually dependent on allowable subgrade pressure, the average pressure exerted on the ballast surface, and tie dimension. Typical empirical equations are given in Table 1. These equations are used to calculate pressure as a function of ballast depth.

Measurements of pressure beneath ties indicate that significant nonuniformities of pressure exist under steel, wood, and concrete ties. The pressure distribution beneath a steel tie is shown in Figure 4.
The total surface width in contact with the ballast (385 mm, as shown in Figure 7) is greater than that obtained with comparable wooden or concrete ties. But nonuniformities in the pressure distribution beneath the tie (in all ties) should be accounted for. To correct for nonuniformities and to obtain maximum allowable ballast pressure beneath the steel tie, an effective bearing width can be calculated by assuming that contact pressures on the surface of the legs are half those obtained on the web section. Effective bearing width \( b \) for the tie in Figure 7 is as follows:

\[
b = 135 + 2[(7 + 41 + 77)/2] = 260 \text{ mm}
\]

Examples of calculated total ballast depth requirements for different types of ties are given in Table 2. The major difference between tie types is the reduced, total ballast depth required for steel ties. Although the data in Table 2 indicate that the steel Trak-Lok™ tie requires greater ballast depth from its centroid than a comparable concrete tie from its base, the overall ballast depth is reduced.

Ballast volume reductions can be calculated by using the equations in Figure 8 with the appropriate inputs. Also, Figure 8 shows the reduced formation width requirement for steel ties (compared to wood and concrete) that may, in some cases, lead to considerable cost savings.

**TESTING FACILITIES**

Full-scale laboratory tests have been conducted at MRL on a number of steel ties, which cover the heavy-haul, main-line, and secondary track ties.

**Steel Tie Testing**

Initially, full-scale tests were performed on pairs
of ties placed on ballast about 0.5 m deep in a box about 5 x 2 m. Loading was provided by slow-acting hydraulic rams capable of operating at only 0.4 Hz. Accelerated testing was achieved by loading the ties with a series of exaggerated loads, such as 0.5 million cycles (MC) at a nominal axle load, 0.5 MC at 1.5 nominal loads, 0.75 MC at 2 nominal loads, and 0.25 at 2.5 nominal loads. A modified version of Miner's rule (1) was used to compute the effective number of cycles at the nominal axle load.

The machine operates at between 10 and 20 Hz, which is approximately equivalent to a train moving at 60 mph; it has a maximum load capacity of 90,000 lb and may be used to test a section of track comprising up to 5 ties. The ballast bed is 5 x 5 x 1 m deep and simulates in-track conditions and provides valuable information on performance of the track structure. The output force of the machine is developed by rotating fly wheels with out-of-balance masses. This machine is operated at appropriate nominal axle load; hence the use of exaggerated loads and Miner's rule (as previously described) was not necessary. (Note that for the convenience of the readers certain measurements of weight and speed were converted to customary units in the text.)

Insulation Pad

The insulation of the two rails that form the track is achieved by using a pad that encloses the rail base. The life of the pad is required to be at least the life of the rail (approximately 10 years in typical high-axle-load conditions). Also, the pad should be adequately stiff so that deflection of the rail during passage of a train in not excessive, and it should be sufficiently resilient to recover its shape and dimensions. Furthermore, the pad must be stable under environmental conditions such as heat, cold, and ultraviolet radiation.

Electrical impedance tests performed in rainfall and under contamination with iron ore dust revealed that early, flat pads lacked sufficiently long elec-
TABLE 2 Tabulated Input Data and Calculated Ballast Depths for Different Types of Ties

<table>
<thead>
<tr>
<th>Tie Type</th>
<th>Timber</th>
<th>Concrete</th>
<th>Steel (other fastening systems)</th>
<th>Steel (Trak-Lok™)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>2.44</td>
<td>2.514</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>229</td>
<td>264</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>Depth (mm)</td>
<td>150</td>
<td>204</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>Depth of centroid (mm)</td>
<td>150</td>
<td>204</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>Rail seat load (kN)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Effective bearing width (mm)</td>
<td>229</td>
<td>264</td>
<td>260</td>
<td>256</td>
</tr>
<tr>
<td>Effective bearing length (m)</td>
<td>2.44</td>
<td>4.514</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>Bearing pressure (kPa)</td>
<td>215</td>
<td>181</td>
<td>185</td>
<td>188</td>
</tr>
<tr>
<td>Allowable subgrade pressure (kPa)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Ballast depth (mm)</td>
<td>449</td>
<td>391</td>
<td>398</td>
<td>403</td>
</tr>
<tr>
<td>Total ballast (mm)</td>
<td>599</td>
<td>595</td>
<td>443</td>
<td>443</td>
</tr>
</tbody>
</table>

1. Exact calculation.  
2. In practice the effective bearing length is less than the actual length of the tie.  
3. See equation for Talbot in Table 1.

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IN ADDITION, THESE PAD MATERIALS WERE SUBJECTED TO CYCLIC LOADING TESTS. RAIL, TIE, AND LOAD ASSEMBLIES RECEIVED THE EQUIVALENT OF MORE THAN 50 YEARS OF IN-TRACK LOADING. THE CYCLIC LOADING TESTS AGREED WITH THE IMPEDANCE TESTS. ONLY HDPE AND POLYURETHANES REMAINED INTACT, WITH NO SIGNIFICANT VISUAL SIGN OF WEAR OR DISTORTION (7).

THE LONG-TERM EFFECT OF ULTRAVIOLET (UV) RADIATION ON A LARGE RANGE OF PADS AND TENSILE SPECIMENS IS BEING STUDIED AT MRL. THESE PADS AND SPECIMENS CONTAIN VARIOUS AMOUNTS OF CARBON BLACK, THE ADDITIVE USED TO INHIBIT DEGRADATION. CURRENTLY, THE HDPE PADS HAVE RECEIVED THE EQUIVALENT OF 10 YEARS OF IN-TRACK RADIATION. IN ADDITION, SPECIMENS CONTAINING 2.5 PERCENT CARBON BLACK (THE STANDARD AMOUNT USED FOR UV PROTECTION) ARE PERFORMING SATISFACTORILY, WITH BARELY PERCEPTIBLE SIGNS OF SURFACE DAMAGE. BECAUSE HDPE PASSED ALL TESTS AND IS LESS EXPENSIVE THAN POLYURETHANE, MRL CHOSE HDPE AS THE PREFERRED INSULATING MATERIAL.

Fasteners

MRL TESTED TIE AND FASTENING SYSTEMS AT THEIR MELBOURNE FACILITY. TWO 10-MM AND ONE 9-MM (TOP THICK-
ties with Omark Trak-Lok™ fastenings were used. A load cycle of approximately 20,250 lb per rail seat was imposed, starting with a minimum of 9,000 lb per rail seat and finishing with a maximum of 29,250 lb per rail seat. The tie and fastener assemblies were examined after $3.0 \times 10^6$ load cycles, and no cracking was evident in the ties or clips, and the insulation pads remained in good condition.

To test lateral resistance, MRL performed creep resistance tests on a new section of rail attached to two ties fixed by clamps and fully clipped. A load was applied at 101 foot pounds per second$^2$ (fib/sec$^2$) longitudinally. A vibrator that fluctuated at 50 Hz was attached to the top of the rail. This vibrator produced a 2,700-lb peak-to-peak oscillation. Lateral resistance ranged from 0.6 to 0.8 at the rail seat load. Figure 12 shows clip load deflection characteristics and a clip diagram. (Note that Figure 12 refers to toe load in kilonewtons. For the convenience of the reader, in the text kilonewtons were converted to fib/sec$^2$.)
Tie Spacings

The allowable number of cycles that may be imposed on a tie is inversely proportional to tie spacing. As tie spacing increases, the allowable number of cycles imposed on that tie decreases. For 20 million gross ton (MGT) traffic, the steel tie recommended by MRL for main-line tracks may be spaced at intervals greater than 600 mm. Ballast depth required at 600-mm spacings is approximately 335 mm from the tie neutral axis.

Minimum Capital Cost Track

Several factors influence the minimum capital cost track, including construction costs, which vary with tie type; actual tie costs (material); ballast volume; and formation width required. The trade-off between tie, spacings, and ballast depth is important because increases in tie spacing (a) decrease the number of ties and the component costs, (b) may increase the ballast depth requirement, and (c) may increase cyclic maintenance costs.

ALTERNATIVE TIE ANALYSIS PROGRAM

Many other factors must be considered in determining costs in an alternative tie analysis. The following calculated steps form the basis of a computer program from Omak Industries that compares cost in steel, concrete, and wood ties:

1. Transportation cost and routing;
2. Rail life extension, if any;
3. Value of second-hand wood tie;
4. First year expenditure or investment;
5. Rate of return as incremental investment to install concrete or steel ties (note that if rate of return is not greater than 5 percent, rail and tie lives are decreased as annual tonnage is increased, based on a ratio dictated by the TOP formula);
6. Present worth of future maintenance expenditures;
7. Annual maintenance savings; and
8. Reduction in possession time required to maintain the track.

The following basic assumptions are used in the analysis:

1. Constant 1982 dollars;
2. Labor costs include full fringe benefits and overhead;
3. All labor and material costs are current as of December 1981;
4. Equipment costs include maintenance, fuel, and capital recovery;
5. The 132-lb rail is replaced with similar rail that requires the replacement of 5 percent plates, 46 percent anchors, and 50 percent spikes;
6. Ballast cost is $5/yd²;

FIGURE 13 Computer printout of investment comparison for different tie types.
7. Transportation of ties and ballast are $0.02 per ton mile on line and $0.06 per ton mile off line; and
8. Work gangs are as follows: (a) wood tie gang—10 machines and 20 men plus distribution and tie pick up, and (b) rail relay gang—18 machines and 48 men plus distribution and rail pick up.

Base data for the analysis are supplied by the railroad. This analysis compares the potential benefits of installing different types of ties on Consolidated Rail Corporation (Conrail) rail lines in the Philadelphia area. Figure 13 shows the computer program investment comparison for different tie types. The savings of steel over concrete is $31,175. Although wood ties create the least expensive initial investment, Figure 14 (the computer program for present worth of future maintenance expenditures) reveals that total maintenance expenditures for 1 mile of track is $69,002 for wood ties, $50,329 for concrete ties, and $45,310 for steel ties. Additional savings for steel accrue from its salvage value.

CONCLUSIONS

1. Steel ties have longer lives than wood ties and, therefore, money is saved on replacement costs.
2. Modern steel ties, fasteners, and insulating pads have been refined to circumvent earlier design inaccuracies.
3. Steel ties are a viable, cost-effective alternative to concrete ties because of low initial cost and ballast savings.
4. Because steel ties weigh less than concrete, savings occur on replacement ties because standard track machinery is required to replace ties. Consequently, money is saved on maintenance.
5. Steel ties have scrap value; wood and concrete ties do not.

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