CONCRETE TIES DESIGNED FOR HIGH DYNAMIC LOADS

Stephan Freudenstein (Dr.-Ing.)
General Manager for Engineering and Development
RAIL.ONE GmbH, Ingolstaedter Strasse 51, 92318 Neumarkt, Germany
Tel +49 9181 28-8670
Fax +49 9181 28-8211
stephan.freudenstein@railone.com
www.railone.com

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ABSTRACT

Throughout the world, railway systems contribute to improving connections among people and facilitating cargo movement. Increasing diversity and density in rail traffic, however, also mean greater demands for cost effectiveness, availability, and lower maintenance expense. Railways represent the most important cargo-transport medium in the USA. This traffic subjects rails and track systems to loads from 286K (130 t) cars, resulting in growing maintenance costs for individual track components.

RAIL.ONE GmbH has developed a new, high-strength concrete tie for 315K (143 t) cars. This tie is designed in accordance with European standpoints, and has been tested by Munich Technical University for static and dynamic properties, and for fatigue behavior. Test results have disclosed complete conformity with European directives, including observance of dynamic loads encountered in the USA.

High dynamic loads and movements of elastic railpads in combination with sand frequently produce abrasion and other wear at rail-support points and on the lower side of concrete ties. Such phenomena lead to costly maintenance and repair of concrete ties: after approx. 2.5 million load cycles, or after only a few years of service – which in turn results in significant impairment of availability and cost effectiveness of the rail line. RAIL.ONE GmbH has therefore developed new ties consisting of special concrete with greater resistance to wear and abrasion in the areas of the rail support points. The company has accordingly modified its production processes to implement this new development. These innovative tie systems increase the life cycle of track systems and appreciably reduce maintenance costs.

INTRODUCTION

The basis for design work for prestressed-concrete ties in Europe is EN 13230 [1], valid since October 2002: “Concrete ties and bearers.” A supplement to this standard is UIC 713 [2]: “Design of Monoblock Concrete Ties,” which provides a design example for a prestressed-concrete tie. The design bending moment calculated here accounts for the dynamic live loads for a track system with a lifetime of 40 years. The tie must be capable of bearing this design moment without cracking.
In the USA, design of prestressed-concrete ties is based on Chapter 30, Part 4, of the AREMA specification “Concrete Ties”, in the version dated 2003 [3]. Here as well, the specification calculates a design moment that the tie must support without cracking. The difference between AREMA and EN 13230 consists in calculation of the design moments, for which more rigorous requirements are specified by AREMA, especially with regard to the rail seat.

The present study describes the salient differences between the two standards – by application of the Cooper E80 freight-train load (used as standard in the USA, see Fig. 1), with a converted maximum axle load of 78 kips (347 kN) – and explains the consequently resulting deviations in requirements placed on the ties. The result of this comparative design project was the creation of a new tie that satisfies the requirements for extremely heavy-haul axle loads: in conformity with both AREMA as well as EN 13230 [4].
DESIGN WHEEL LOAD

The design wheel load, also known as dynamic support-point force, is the force that acts on the tie and that, in turn, produces the design moment. In bending tests, the concrete tie must be able to withstand this design moment without the formation of cracks. The design load is calculated from the static wheel load $Q$ of the train, which makes up 50% of the axle load: i.e., 39 kips (173.5 kN). This force is furthermore influenced by the dynamic factor $\gamma_{v}$, which takes the speed and faults in vehicle geometry into consideration: e.g., wheel flats.

With respect to the dynamic factor, EN 13230 distinguishes only between speeds up to 124 MPH (200 km/h), and speeds greater than 124 MPH (200 km/h). For design purposes, assumption is made of a maximum speed of 100 MPH (160 km/h). Under these conditions, $\gamma_{v} = 0.5$; for $v \geq 124$ MPH (200 km/h), $\gamma_{v}$ would equal 0.75. It is, furthermore, possible to take into account the damping effect $\gamma_{p}$ of the rail-fastening system. Employment of an elastic rail pad attenuates dynamic effects and enhances distribution of the applied load onto several ties as a result of rail deflection. This, in effect, reduces the loads applied to each of the individual ties. Since elastic rail pads are not used for standard ballasted tracks, low attenuation of $\gamma_{p} = 1.0$ is applied in calculations for such tracks, to provide an additional margin of safety. For medium damping levels, the factor is approx. 0.89; for high damping, around 0.78. These two values are used to calculate the combined dynamic factor as follows:

$$\gamma_{vp} = 1.0 + \gamma_{v} \cdot \gamma_{p} = 1.0 + 0.5 \cdot 1.0 = 1.5$$

Partial safety coefficients, furthermore, are also taken into account here. The first such factor is $\gamma_{r} = 1.35$ for flaws in track substructure: e.g., asymmetric support (cavities in the ballast) under the ties. The second such factor is $\gamma_{i} = 1.6$ for faults in track positioning: for example, irregular placement of the ties. This results in a total safety coefficient of 2.16. An additional essential aspect is the load-distribution effects of the rail. For tie pitch (i.e., interval between the ties) up to 26.6 in (650 mm), and for a rail with a mass greater than 93 lb/yd (46 kg/m), a factor of $\gamma_{d} = 0.5$ is applied: i.e., 50% of the wheel load acts directly on the tie located immediately beneath the wheel, with 25% acting on each of the two adjacent ties. Consideration of all these factors results in a total dynamic coefficient of von $\gamma_{tot} = 1.5 \cdot 2.16 = 3.24$ to be applied to the static wheel load. This enables calculation of the design load, in accordance with EN 13230, as follows:

$$P_{d} = Q \cdot \gamma_{tot} \cdot \gamma_{d} = 39 \text{ kips (173.5 kN)} \cdot 3.24 \cdot 0.5 = 63 \text{ kips (280kN)}$$
The dynamic and load-distribution factors are also calculated for the design wheel load in work carried out in accordance with AREMA. Unlike work performed in accordance with EN 13230, however, calculations on the basis of AREMA do not apply a general assumption of 50% for load-distribution effects: instead, the percent employed is selected as a function of the tie pitch (interval) (Fig. 2). For typical tie-pitch values of 23.6 in to 26.6 in (600 to 650 mm), the load distribution factor will lie between 49 and 53%. With the factor of 50% as used with EN 13230, therefore, calculations on the basis of this standard are based on a tie pitch of 24 in (610 mm). In work with AREMA, greater values result in conjunction with larger tie intervals: i.e., the load-distribution factor and, in turn, the tie load, become larger. AREMA does not enable exact calculations with account taken of the rail or the ballast reaction. This, however, is possible by application of the Winkler-Zimmermann method, in accordance with the theory of an elastically supported beam. For the further calculations to be performed in the present study, a tie pitch of 24 in (610 mm) will be employed, in order to obtain a load-distribution factor of 0.5 for both standards.

![Fig. 3: Load distribution on the basis of AREMA, Section 4.1.2.3](image)

For the dynamic wheel load in accordance with AREMA, a general factor of 200% is applied to the static wheel load. This influencing factor (IF) arises as a result of the dynamic effects of the wheel and of the rail and/or track faults. Accordingly, the design wheel load is calculated as follows:
\[ P_d = Q \cdot (1.0 + IF) = 39 \text{kips} (173.5 \text{kN}) \cdot \left( 1.0 + \frac{200}{100} \right) \cdot 0.5 = 58 \text{kips} (260 \text{kN}) \]

Although this result for the design wheel load is less than that calculated with EN 13230, an additional factor comes into play with AREMA. This represents the greatest difference in the influencing variables, since the annual tonnage is considered here, and the speed is exactly taken into account (Fig. 3). Whereas EN 13230 draws distinctions only above and below the speed of 124 MPH (200 km/h), AREMA calculations exactly determine the speed factor. A factor of \( V = 1.1 \) results on the basis of a speed of 100 MPH (160 km/h). AREMA, furthermore, determines an influencing factor as a function of the annual tonnage: a factor not taken into account by EN 13230. For annual tonnage of 75 million gross tons (MGT), the tonnage factor would also be \( T = 1.1 \). This results in a total factor, for speed and tonnage, of \( V + T = 1.21 \). Work with AREMA therefore leads to a total factor of 3.6 to be applied to the static wheel load, in comparison to 3.24 obtained with EN 13230. The design wheel load is accordingly greater: 71 kips (315 kN) instead of 63 kips (280 kN). The further calculations are based on this greater wheel load, in order to achieve comparable results in moment calculations.

![Fig. 4: Tonnage and speed factors in accordance with AREMA, Section 4.4.1.2](image-url)
DESIGN MOMENTS

The design wheel load as determined above is now used to calculate the design moments. EN 13230 takes into account two loading cases of primary importance. The first case involves freshly tamped ties. In this case, ballast compaction takes place only in the area of the rail seat (Fig. 4). The length of ballast compaction is equal on both sides of the rail. For this loading case, the greatest positive moment occurs at the lower side of the tie.

Fig. 5: Load case no. 1

In calculations of the design moment under the rail, EN 13230 stipulates a rounded transition between moment curves: i.e., the application of loads takes place over the rail seat, and not at a single point. EN 13230 further specifies here that the force applied be attenuated under an angle of 45°, up to a point at approximately half the tie height (Fig. 5). In this way, the width of the rail seat and the tie height will influence the moment, since the introduction of loads is changed as a function of rail-base width and tie height. The length of the tie likewise has an effect, since the projecting end of the tie \( L_p \) will change, thereby modifying the length of the lever arm. The tie length can be shortened to reduce the moment. This, however, has the result that the moment will increase at the center of the tie. This effect is then taken into consideration in the second loading case of primary importance. For loading case no. 1, the positive design moment is calculated as follows:

\[
M_{dr+} = \frac{P_d}{4} \left( L_p - \frac{f}{2} - \frac{h}{2} \right)
\]

Fig. 6: Positive design bending moment according to EN 13230
AREMA does not take this application of loads into consideration. The plot of moments shown in Fig. 6 makes clear this major difference between the two standards. This plot was calculated for a tie 2.6 m long, with a design wheel load of 71 kips (315 kN). These calculations were further based on a UIC 60 rail, with rail seat 5.9 in (150 mm) wide and a tie height of 9.2 in (233 mm) under the rail. A value of 383 inch-kips (43.3 kNm) results without rounded transition between moment curves (shown in Fig. 6 as “without reduction”); with the rounded transition, the value is 253 inch-kips (28.6 kNm) (shown in Fig. 6 as “with reduction”). This is approximately equivalent to a reduction of 34%.

![Fig. 7: Plot of positive bending moment at rail seat](image)

The AREMA specification does not furnish formulas for calculations of the moments. Instead, it provides graphs for the design moments, with various tie lengths and tie pitches (Fig. 7). The tonnage and speed factor V + T has not yet been applied to these values, however: i.e., the moments are provided here for a design wheel load of 58 kips (260 kN), and must later be multiplied by the V + T factor of 1.21. For a tie length of 2.84 yd (2.6 m) and a tie pitch of 24 in (610 mm), this diagram shows an unfactored positive bending moment of approx. 303 inch-kips (34.3 kNm). Application of the tonnage and speed factor V + T yields a result of 367 inch-kips (41.5 kNm). This procedure produces approximately the same moment as with calculations in accordance with EN 13230 and without rounded transition between moment curves. This reveals that the two calculation methods yield approximately the same values for the positive design moment under the rail seat. Work with EN 13230, however, involves an additional reduction as a result of the application of forces, which means that requirements
decrease by approx. 31%, i.e., from 367 inch-kips (41.5 kNm) (according to AREMA) to 253 inch-kips (28.6 kNm) (in accordance with EN 13230).

Fig. 8: Unfactored positive bending moments at rail seat, AREMA Section 4.4.1.1

In the second load case, uniform ballast compaction takes place under the entire tie. This condition arises after relatively long track operational time, after the dynamic processes of passing trains acting on the system distribute and compact the ballast under the tie (Fig. 8). Under these conditions, the tie begins to “ride,” and the largest negative moment occurs at the upper side, in the middle of the tie. The tie bedding area and the length of the tie play a major role here. A waist at the middle of the tie offers the advantage (Fig. 9) of a reduction in load and in moment. The following equations allow calculation of the negative moment, in accordance with EN 13230, for ties with and without waists:

Without waist: \[ M_{dc-} = \frac{P_d}{4} \cdot (2 \cdot g - L) \]

With waist: \[ M_{dc-} = P_d \cdot \left[ g \cdot \frac{L}{2} + \frac{b_1 \cdot L^2}{8} + b^2 \cdot \left( \frac{k^2 + c \cdot k + c^2}{3} \right) \right] \]
The AREMA specification contains a graph for calculation of the negative moment at the middle of the tie (Fig. 10). This diagram shows the negative moment to be a function of the tie length and of the positive moment. These values are based on a tie with a uniform width: i.e., a tie without a waist. For a length of 2.84 yd (2.6 m), for example, the negative moment at the middle of the tie is 65% of the positive moment at the rail seat. In other words, with the value of 367 inch-kips (41.5 kNm) calculated above for the positive moment at the rail seat, a negative moment of approx. 239 inch-kips (27.0 kNm) will occur, according to AREMA, in the middle of the tie. On the basis of AREMA, a waist in the middle of the tie can be expected to result in a reduction of approx. 10%. If the moment is calculated for the exact tie bedding area for load case no. 2, in accordance with EN 13230, and with a design wheel load of 143 kips (315 kN), a moment of 279 inch-kips (31.5 kNm) results for a tie without a waist. This signifies that the values specified in EN 13230 are approx. 17% greater here than those contained in AREMA. For a tie with a waist, the moment decreases to 219 inch-kips (24.7 kNm): i.e., a reduction of the AREMA moment by 10%. The following conclusion is therefore justified here: for ties with uniform width, the specified values for the tie middle as set forth in EN 13230 are approx. 17% greater than the requirements in accordance with AREMA – whereas the two standards provide approximately the same results for work with ties with waists.

As stated in conjunction with calculation of the positive moment in the rail fastening, the plots of the curves here clearly reveal that a reduction in tie length causes a pronounced increase in the negative moment at the middle of
the tie. This consequently signifies that the selection of tie length plays an essential role in achieving harmony in the two standards. A long tie produces a large positive moment at the rail fastening; with a short tie, in contrast, the requirement placed on the negative moment at the tie middle becomes more rigorous. Harmony is achieved here for tie lengths of 7’9” to 9’0” (2.36 m to 2.74 m).

![Graph of bending moments](image)

**Fig. 11: Calculation of bending moments, in accordance with AREMA, Section 4.4.1.2**

This diagram additionally provides the data for the negative moment in the rail fastening, and for the positive moment at the middle of the tie. EN 13230 does not require testing for these values, or it classifies such testing as optional. The present study will therefore not further consider these two moments.

In order to satisfy both the stringent specifications set down by AREMA, as well as those by EN 13230, a new tie has been developed: the UP 04 (see Fig. 11), which conforms to the respective maximum requirements in both standards. The table below once again recapitulates the various specifications for an axle load of 78 kips (347 kN). This table takes into account the various calculation techniques contained in the two standards: for design wheel load and for the design moments. The first column shows the specifications as set down in AREMA, with constant width of the ties, and without rounded transition between moment curves. The next two columns give the design moments according to EN 13230: each with and without rounded transition between moment curves (“moment reduction”) under the rail fastening, and with and without a waist at the middle of the tie (“reduced center”) – but with the design wheel load as per AREMA. The fourth column, in contrast, shows
the requirements placed for 78 kips (347 kN) axle load, which have been entirely calculated in conformity with EN 13230: i.e., with less design wheel load. The fifth column provides the results of calculations for an axle load of 99 kips (440 kN), in accordance with EN 13230. The fifth column details results for the actual moment causing cracking for the UP 04, as determined in testing at Munich Technical University. These data unquestionably demonstrate that this new tie performs appreciably better than the requirements placed by AREMA. It is furthermore evident that the requirements for axle load of 99 kips (440 kN) are likewise fulfilled. Official certification tests were also conducted in accordance with EN 13230 for this axle load at Munich Technical University: tests which were successfully passed.

Table 1: Overview of the specifications of both standards

<table>
<thead>
<tr>
<th>Axle load [kN]</th>
<th>78</th>
<th>99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>AREMA</td>
<td>EN 13230</td>
</tr>
<tr>
<td>Design Wheel load [kN]</td>
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<td>63</td>
</tr>
<tr>
<td>Moment reduction</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>reduced centre</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Required Design Bending Moments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Results</td>
<td>367,0</td>
<td>383,0</td>
</tr>
<tr>
<td>Rail Seat Positive [inch-kips]</td>
<td>367,0</td>
<td>383,0</td>
</tr>
<tr>
<td>Center negative [inch-kips]</td>
<td>239,0</td>
<td>279,0</td>
</tr>
</tbody>
</table>
TIE TESTS

Further differences between AREMA and EN 13230 arise in conjunction with official certification testing. Bending tests in accordance with AREMA, for example, are performed on only one tie. Here, positive and negative bending tests are first conducted at both rail fastenings, and in the middle of the tie: i.e., for a total of six static bending tests. The stipulations for AREMA static bending tests require application of the design moment without the appearance of cracks in the tie. This procedure represents the entire sequence for the static bending test; this test comes to an end at this point. Certification testing as per AREMA next involves fatigue testing for one rail fastening: by application of loads until the tie cracks up to the first prestressing tendon. Three million loading cycles are subsequently applied to the tie, whereby the peak load applied in each load cycle amounts to 10% more than the design moment. The tie passes the test if, after 3 million loading cycles, it can withstand, without breaking, a moment that is 10% greater than the design moment. The last AREMA test is an ultimate-strength test performed on the other rail fastening, whereby the breaking moment is stipulated at only 50% above the design moment. All these specifications signify that a tie must undergo a total of 8 bending tests.

For testing in accordance with EN 13230, the stipulations for testing differ radically from those in AREMA, with regard to the number of test ties alone. EN 13230 calls for the testing of no fewer than a total of 16 ties: whereby only one test may be performed on each tie. Static bending tests are performed on 6 rail fastenings for positive moment, and on the centers of 3 ties for negative moment. In this testing, the tie is loaded with the design
moment, and must not crack here as well. Unlike AREMA, the cracking moment according to EN 13230 is determined for each tie. Furthermore, EN 13230 stipulates the moment for the rail fastening for which the crack must re-close to such an extent that the crack width is less than 0.002 in (0.05 mm) upon removal of the test load. In addition, this standard specifies the breaking moment at the rail fastening for the six ties. The design moment must be multiplied by the $k$ values for determination of these moments. EN 13230 establishes these $k$ values, for example, as 1.8 for the 0.002 in (0.05 mm) cracking moment in a non-loaded state, and 2.5 for the breaking moment. This evidences that the testing specifications are appreciably more demanding in EN 13230 than in AREMA: in comparison, for example, the breaking moment for AREMA is 1.5 times the design moment, and for EN 13230, it is 2.5 times the design moment.

In addition to the static tests, EN 13230 requires 6 further dynamic tests performed at the rail fastening. In the EN 13230 dynamic testing (not stipulated by AREMA), the procedure is carried out analogous to that for static testing: i.e., here as well, the cracking moment, the 0.002 in (0.05 mm) crack-width moment for a condition without loading, and the breaking moment all must be determined – to be sure, with lesser $k$ values (1.5 and 2.2). The final required test is an ultimate-strength test, for which loading is likewise applied until cracking appears. Subsequently, the ties are subjected to 2 million load cycles, with loading for each tie up to the design moment. EN 13230, however, sets the stipulations that the crack under load must be smaller than 0.004 in (0.1 mm), and less than 0.002 in (0.05 mm) without loading. This standard also determines the breaking moment for the following ultimate-strength test.
RAIL SEAT ABRASION

High dynamic loads and movements of the railpads in combination with sand frequently produce abrasion and other wear at rail-support points and on the lower side of concrete ties. Especially on heavily loaded coal lines, abrasion on concrete ties has been detected in the rail seat area (Fig. 13).

Fig. 13: Sail seat Abrasion on concrete ties

Dynamically acting vertical forces expand and contract the elastic pads between the rails and the concrete surfaces. In the presence of water and sand (i.e., most likely sand from the locomotives), high friction forces act on the concrete surfaces. This leads to erosion of the concrete and the fastening elements. Problems consequently arise when individual fastening components break, or rail deflections on the rail seats occur.

An abrasion test for concrete ties has been developed to help solve these problems from the standpoint of the tie manufacturers. The test features sandblast equipment with defined pressure, sand, and test conditions, and is designed to produce erosion defects on the concrete ties similar to those observed in actual operation. This test procedure enables determination of the mass of eroded material as a function of time. By means of this investigation, it has proved possible to develop special abrasion-resistant concrete that can now be used for concrete ties. Owing to economic constraints, however, it is not possible to use this special concrete for the entire ties. The next step of development was to determine a technique to enable use of the expensive concrete only in the necessary area. RAIL.ONE has developed production technology in which only a small amount of the special concrete is required. A small quantity (i.e., a bucket of a particular size) of this concrete is utilized for filling at the rail-seat area, with retention of normal tie concrete for the remainder of the tie. Concrete, however, is
required immediately after pouring the first layer. This technique guarantees full bonding between the two concrete layers (Fig. 14).

**Fig. 14: Abrasion-resistant concrete in the rail seat area**

After demolding, the two concrete types become visually apparent by virtue of their different colors. Both concretes must demonstrate equal shrinkage behavior, to prevent cracks at the transition zone between the two concrete types (Fig. 15).

**Fig. 15: Ties with two different concrete layers**
During recent years, numerous tests have been conducted in Germany on such ties with two layers of concrete. The development process, supervised by Munich Technical University, enabled creation of a solution to ensure superior rail-seat abrasion behavior on ties, with strict observance of economic constraints.

**SUMMARY**

The stipulations set in the USA for ties at the rail seat are appreciably more demanding than those in Europe: partially as a result of the very high stipulated axle load of 78 kips (347 kN). For design work with this axle load performed in accordance with EN 13230, the design moments are still approx. 31% lower than the requirements stipulated by AREMA. This value is the consequence of the lack of rounded transition between moment curves under the rail fastening. At the same time, however, the requirements placed for the center of the tie are approx. 17% less in the USA than in Europe. These circumstances have practical consequences: in the USA, for example, problems primarily appear at the center of the tie in prestressed-concrete ties. In order to satisfy the stipulations contained in AREMA as well as in EN 13230, a new tie was designed: the UP 04. For design work in accordance with AREMA, this new tie conforms to the requirements for an axle load of 78 kips (347 kN). In work on the basis of EN 13230, the permissible axle load can be increased to 99 kips (440 kN). Tests have already been conducted at Munich Technical University for these high axle loads, which resulted in successful passing of tests for axle loads of 99 kips (440 kN) as stipulated by EN 13230. The rail-seat abrasion problem has been solved by newly developed production technology featuring two different concrete layers. In the rail-seat area, small amounts of special abrasion-resistant concrete are now employed; immediately after placing this concrete, the other zones of the ties are concreted with standard tie concrete.

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Table 1: Overview of the specifications of both standards