CASE STUDIES IN RAILWAY CONSTRUCTION

EMBEDDED RAIL STRUCTURES
The characteristics of embedded rail

- Embedded Rail Structure (ERS) involves continuous support of the rail by means of a compound e.g. consisting of cork and polyurethane. The rails are fixated by means of this elastic compound which surrounds almost the entire rail profile except for the rail head. Characteristic of this concept is the lack of additional elements to secure track gauge. This concept can cover the full range from light rail to high-speed tracks.
The method of rail fixation is characterized by the following principles:

- Continuous support of the rail on an elastic strip;
- Guiding of the rail by elastic fixation in a groove;
- Top-down alignment of the rails;
- Fixation of the rail profile by an elastic poured compound;
- Design optimization of the groove dimensions, elastic compounds, and strips for specific elasticity.
• The advantages of an elastic continuous supported rail are the absence of dynamic forces due to secondary bending between single rail supports, reduction of noise production, increase in life span of the rails, and further reduction of maintenance. The construction height can be reduced for road crossings, so that embedded rail provides a smooth and obstacle free surface for crossing traffic.
Construction of embedded rail track

- Embedded rail needs a groove to contain the poured elastic compound and the rail. Such a groove can be provided by concrete or steel. In the latter case, one could think of steel bridges or U-steel profiles cast in concrete. For paved-in track or main-line track, a concrete slab provides the support for the embedded rail. The next figure shows the cross-section of a detail of a slab containing the embedded rail.
Detail of an embedded rail inside a groove
• Using a slipform paver, a continuous concrete slab is made. Because there is hardly any possibility to readjust the rail afterwards, the soil must be free of settlement.

• The slab contains the grooves; the position of the slab determines to a very large extent the horizontal alignment, the direction, the track gauge, and the twist of the track. The production of the slab, therefore, demands high precision. The next figure shows the final stage of construction of a continuous reinforced concrete slab using a slipform paver.
Slipform paver
• At the bottom of the groove an elastic strip is laid on top of which the rail is positioned in the groove with filling pads underneath the rail foot and elastic wedges to the sides. The rail is adjusted by means of a top-down method.

• After adjustment, the rail is made stress free by means of heating before the compound is poured into the groove.
Pouring of the compound into the groove
Experiences with embedded rail

• Many pilot tracks of embedded rail have been applied over the last 30 years, 246 m paved-in as well as main-line track. Nearby Deurne (The Netherlands) in 1976, a pilot was constructed in heavily used track with speeds up to 160 km/h. The track existed of a series of 6 meters of prefabricated slabs containing the gullies supported underneath with old NP46 rails. The experiences were qualified as positive. In 1994, the rails were renewed, but the wear of those rails was considerably less compared to the adjacent track.
• Another large pilot concerned 3 km track nearby Best (The Netherlands) which came into operation in October 1999 and is currently being monitored.
• The superstructure consists of a 42 cm thick slab with longitudinal reinforcement providing the slab with a high flexural strength. The slab lies on top of a concrete road bed and stabilized subsoil. The cross section of this track structure is shown in the next figure.
Cross section of the embedded rail superstructure near Best
Construction process of this test track
Installing of the rails
Positioning of the rails by means of wedges
Electrical heating of the rails (17 °C)
Pouring of the compound into the groove
Explanation

• As the rails are fully embedded the maximum rail temperature remains substantially lower than with a built-up structure. This, in combination with the large lateral rail resistance, was the reason to lower the neutral temperature from normally 25 °C to 17 °C.
Track after completion
Slab covered with ZOAB asphalt for noise absorption
• As part of this project an innovative rail design was also tested using the so-called low-noise Rail. As a result of an optimization process and component testing a -5 dB(A) noise reduction was achieved. Moreover, this design uses only 40% of the elastic compound normally used with UIC54 rails to secure the rails.
Low-noise rail SA42
• In 2000, a 256 m paved-in double tramway track was constructed in The Hague (The Netherlands) on top of soft soil. The local situation posed the designers for certain problems because of plans for future earthworks adjacent to and underneath the slab, such as conveyance of pipes by pressing.
Reinforcement inside the slab for embedded rail meant for tramway application in The Hague
• The slab was therefore reinforced to such an extent that it would be able to withstand local subsiding of the supportive layers of soil over a length of 2 meter. A slab with a high flexural strength was necessary because of uncertainties due to future building activities next to the track. Time consuming extensive soil improvements could be omitted.
Another specific application of embedded rail, in use since 1974, are the "Harmelen" level crossings. These level crossings consist of a single slab with a length of 6 or 9 meters which is lowered into a ditch partly filled with sand and adjusted in height.
Installation of a Harmelen level crossing
• Afterwards, the remaining void between the sand and the slab is injected with quickly hardening hydraulic mortar. Embedded rail thus provides an obstacle and maintenance-free level-crossing.
DeckTrack

• An example of an embedded rail structure with very high flexural stiffness is called "DeckTrack". DeckTrack has been specifically designed for use on soft soils and consists of a continuous in-situ or prefabricated concrete bearer laid into the ground.
Artist impression of the Deck Track system
• On top, the rails can be directly applied as embedded rail or by means of direct fastening. The concrete deck can be considered as a hollow tube weighing more or less the same as the mass of the removed soil. No settlement will occur as a result of the structure’s weight.
• The high bending stiffness of the structure avoids differential settlements and reduces vibrations. High torsion stiffness provides a stable basis for the track, even on soft soils. Local subsidence of the track is precluded. Local lack of bearing strength in the subsoil will not cause problems as DeckTrack is able to act like a bridge and cover these weak spots. The high stiffness over the mass ratio causes little vibration to be transmitted into the soil and makes DeckTrack a suitable structure for high-speed traffic and for application on soft soils.
DeckTrack is perfectly suitable for the use of embedded rail. With the use of the dedicated rail profile SA 42, noise emission can be reduced to the level of conventional ballasted track. The structure can be cast in situ as a continuous beam, assembled from prefabricated elements linked at the joints, or as a combination of both. Both methods lend themselves to a high level of mechanization.
Currently, a 200 m test track in Rotterdam (The Netherlands) is being monitored regarding the long-term settlement of the track. Traffic loading of the track causes uniform but limited soil settlements. While the track structure is directly connected to the concrete structure, the same positioning and deformation requirements that apply to a track will apply to the concrete structure as well. The test has shown that the track geometry remains the same quality as after construction for a lengthy period and that the track quality does not deteriorate significantly in spite of settlements of the structure.
Test track in Rotterdam
Testing of the UIC54 ERS

- Several case studies were performed at the Technical University Delft using the ANSYS software on ballastless track structures with a special concentration on the Embedded Rail Structure (ERS). Initial calculations of ERS using the ANSYS program were made with the "standard" ERS, i.e. the ERS with UIC 54 rail, Edilon prefab elastic strip nr. 102, and Edilon Corkelast compound VA60, as shown in the next figure. The aim of this investigation was to devise and calibrate a numeric FEM-based model of ERS, which could be reliably used in future to reduce the number of long and expensive laboratory tests.
Standard UIC 54 Embedded Rail Structure
• The calibration of the model was performed by comparing the obtained numeric calculation results with the ones previously obtained in laboratory. Applied loads complied with the NS regulations regarding testing of the track elasticity of Embedded Rail Structures, i.e. with the loads applied in the vertical, sloped (22 and 31 degrees), and longitudinal direction, as shown in the next table and in the next figure.
Tests determining the elasticity

<table>
<thead>
<tr>
<th>Test</th>
<th>Angle</th>
<th>Load</th>
<th>Type of Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0°</td>
<td>$V=P$</td>
<td>Static</td>
</tr>
<tr>
<td>1b</td>
<td>0°</td>
<td>$V=P$</td>
<td>Static &amp; dynamic</td>
</tr>
<tr>
<td>2</td>
<td>22°</td>
<td>$V=P$, $H=0.4\cdot P$</td>
<td>Static &amp; quasi-static</td>
</tr>
<tr>
<td>3</td>
<td>31°</td>
<td>$V=P$, $H=0.6\cdot P$</td>
<td>Static &amp; quasi-static</td>
</tr>
<tr>
<td>4</td>
<td>0°</td>
<td>$V=P$</td>
<td>Static</td>
</tr>
</tbody>
</table>
Testing with different loading cases
Some of the essential results of this study were:

• The ANSYS FEM calculation could reliably describe the results of laboratory tests on stiffness and strength of ERS, hence it could be used instead of multiple testing of intermediate designs. Thus, the laboratory work can be restricted to only performing tests on the final design.

• The obtained results not only staid within a 5% margin, but were even less compared to the laboratory tests. This means that the ANSYS FEM calculations could be successfully used to reduce the laboratory tests. However, calibration of the FEM with a corresponding laboratory test still remains a necessary prerequisite in order to use it.

• In the Standard ERS with UIC54 rail, the elastic pad could not be replaced by a softer compound material due to the resulting high lateral displacements.
• The successful completion of the UIC54 ERS prompted the continuation of the research, this time directed towards the innovative ERS structures, e.g. the ones with SA37 and SA42 rails and subsequently those with even more non-standard rail types and various compound characteristics. The reason for taking this direction was the firm belief that the standard UIC54 ERS offered a lot of opportunities for further optimization. The first two objectives were to investigate the possibility of replacing the elastic strip with a softer type of compound and reducing the total amount of the compound, both of which would reduce the cost of a structure and simplify the construction.
Testing of the SA42 ERS

• The first step in testing SA42 ERS was to perform the verification of the FEM numeric model. In order to verify the numerical model, the available testing results of the 250 mm long sample of ERS with a low-noise rail SA42, compound VA90, and elastic strip fc6-sp have been used.
Laboratory testing of ERS at Delft University of Technology
A 3-D model of this structure created in ANSYS is shown in the next figure. E-moduli of the compound and strip have been determined by fitting the responses of the numerical model into the results of the laboratory tests. One of these responses is the vertical displacement of the rail which should be 2.1 mm if a vertical load of 30.4 kN is applied.
3-D finite element model of SA42 ERS
2-D finite element model of SA42 ERS
• Although the 3-D model can accurately describe the experiment, due to high computational costs it was practically impossible to use it in the optimization process where multiple evaluations of the structural responses are required. That is why a 2-D model has been created assuming that in the middle of the ERS sample the model satisfies the plane strain condition. The results of the 2-D model have been compared with those obtained using the 3-D model. They are collected in Table 5.12 which shows that a difference of about 10% exists between the calculated vertical displacements of the 2-D and 3-D models.
• This comparison has proven to be very stable regardless of the geometry of ERS, the type of elements, and the mesh density used in the numerical model. A comparable relationship was also obtained for the ERS model and the UIC54 rail. The obtained ratio was then used as correction-factor during the optimization in order to estimate the displacements of the 3-D model based on the results of the 2-D model.
The calculated maximum stresses in the compound were obviously more dangerous in the angular loading case than in the pure vertical loading case. However, experiments have proven that these stresses were allowable (safe) since no cracks occurred during the corresponding static (both UIC54 and SA42 rails) and fatigue (only SA42) laboratory tests. In addition, it turned out that for stiffer compounds higher levels of stresses could be tolerated (before the compound cracked).
2-D and 3-D calculation results of SA42 ERS in ANSYS

<table>
<thead>
<tr>
<th>Loading types</th>
<th>Vertical displacement at loading point [mm]</th>
<th>Maximum Von Mises stresses in compound [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-D results</td>
<td>3-D results</td>
</tr>
<tr>
<td>Vertical load 30.4 kN</td>
<td>2.29</td>
<td>2.29</td>
</tr>
<tr>
<td>Angular load (22 degrees) Vertical component 30.4 kN</td>
<td>2.70 lateral: 0.40</td>
<td>2.48 lateral: 0.41</td>
</tr>
<tr>
<td>Lateral component 12.2 kN</td>
<td></td>
<td></td>
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</tbody>
</table>
Input and output of static model

• In order to analyze the static behavior of embedded rail structure in ANSYS, the numerical model requires the input of the following parameters:
• Geometry of ERS, i.e. the exact shape of the rail, trough, and level of compound;
• Material properties of the rail and the compound. For the rail, well-known steel material properties have been used. For the compound, both E-modulus and Poisson’s ratio are parameters to be optimized;
Two loading cases have been considered, namely a vertical load of 30.4 kN acting in the middle of the rail head (to determine track stiffness) and an angular load (22 degrees relative to vertical) of 32.4 kN (to evaluate the lateral movement of the rail). The latter load which represents wheel loading in wide curves can be split up into a 30.4 kN vertical and a 12.2 kN horizontal load.
Results

Some of the essential conclusions of the SA42 ERS investigation were:

• As in the case of UIC54 ERS, ANSYS FEM calculation reliably described the results of laboratory tests on stiffness and strength of ERS;

• In order to reduce the calculation time a 2-D model has been created. After a comparison with the 3-D model, a difference of about 10% was found to exist which remained stable regardless of the geometry of ERS, type of elements, and mesh density used in the numerical model. This was a good enough reason to use the 2-D model in cases when preliminary results were sought or when a large number of calculations had to be performed, e.g. during the iterative optimization process;
• The elastic pad, which is a common part of current designs, was now replaced by the appropriate type of elastic compound. The reason for this was that during the initial calculations with the SA42 ERS design a simple optimization was performed within ANSYS. The results of this optimization showed that due to the considerably lower height of the SA42 ERS, comparable behavior could be achieved by only applying the compound with adapted E-modulus and Poisson’s ratio values.
Optimal design of embedded rail structure (ERS)

In this Section a procedure used for optimal design of a railway track is presented which has been developed at Delft University of Technology. The procedure contains all necessary parts of the design process, such as:

- Numerical modeling of track behavior;
- Verification and calibration of a numerical model using results of laboratory tests;
- Optimization.
• Here, the procedure is applied to the optimal design of an Embedded Rail Structure. The criteria regarding optimal design are based on the requirements to railway tracks relating to the design's cost efficiency, minimum noise emission, and minimum wear of rails and wheels. The design variables comprise the material and geometry properties of ERS, namely elastic properties and volume of compound, shape of rails, and size of troughs. The static and dynamic behavior of ERS is analyzed using the finite element models built using ANSYS and RAIL.
In the subsequent sections the following topics will be discussed:

• Requirements for optimum design of ERS and its numerical interpretation;
• Choice of optimal design criteria;
• Formulation of an optimization problem;
• Formulation of a multi criteria optimization problem;
• Obtaining results.
• A typical ERS consists of a continuous reinforced concrete slab that rests on a concrete stabilized road bed, which in turn is placed on a sand base. Two (conventional) rails are embedded in visco-elastic compound (polyurethane mixture) for which two troughs are made in the slab.
Embedded Rail Structure (ERS)
Requirements for optimum design of ERS

Here the response quantities relating to cost efficiency, acoustic properties, and maintenance effort are considered of importance to the optimum performance of ERS. To estimate the performance of an ERS design, static and dynamic models have been developed. The static response quantities such as stresses and displacements of an embedded rail structure under various loading conditions have been obtained using a general purpose finite element package ANSYS.

The 2-D and 3-D FE models of ERS are shown in the next figure. Before these models were included in the optimization process, they were verified by comparing the results of laboratory tests and finite element calculations.
3-D and 2-D finite element models of ERS with SA42 rail
In order to ensure that the static and dynamic models describe the behavior of the same ERS, they have been coupled to each other by adjusting geometrical properties such as cross-sectional moment of inertia, etc. of the rails in the dynamic analysis based on the parameters of the static model. Also, the static and dynamic vertical stiffness of ERS has been correlated. To determine the static stiffness of a track the vertical load $F_y$ has been applied at the top of the rail head as shown in.
• The static ($K_{\text{stat}}$) and dynamic ($K_{\text{dyn}}$) vertical stiffness are then calculated as $K_{\text{stat}} = F_y/u_{y,1}$ and $K_{\text{dyn}} = 2K_{\text{stat}}$ ($u_{y,1}$ is the vertical displacement of the rail corresponding to this loading case).
Loading cases for static analysis (ANSYS) of ERS
Minimum cost requirement

• The cost efficiency of ERS can be estimated by the amount of elastic compound used in it. To reduce the costs, the volume of elastic compound $V \, [\text{dm}^3/\text{m}]$ used in ERS should be minimal.
Minimum acoustic noise requirement

• The 'open surface' of ERS, i.e. the surface of the rail and the elastic compound that is in contact with open air, defines the level of the acoustic noise. The noise radiating from the ERS structure increases in proportion to the size of the open surface. Thus, in order to reduce the noise produced by a structure, the open surface of ERS [dm²/m] should be minimized.
• An optimum railway track should possess good dynamic properties. Large vibrations on a track can diminish passengers’ comfort and increase maintenance effort of vehicles, rails, and other structures. To avoid the harmful track vibrations, resonant frequencies of ERS should not coincide with any of the vehicle resonant frequencies. One way to achieve that is to shift the resonant frequencies of a track as far as possible from those of a vehicle. In other words, the first principal resonant frequency of ERS in vertical direction should be maximized.
• It should be noted that the acoustic characteristics of ERS (i.e. the ability of a track to damp vibrations before it starts to radiate them via its open surface) improve as the first resonant frequency is increased. The resonant frequency $f_r$ is obtained by applying an impulse load to ERS and performing the frequency response analysis.
Since the level of acoustic noise radiating from ERS depends on both the resonant frequency $f_r$ and the area of the open surface, the following formula has been used to estimate the acoustic noise $F_N$:

$$F_N = A \frac{f_{max} - f_r}{f_{max} - f_{min}},$$

which $f_{min} = 100$ Hz and $f_{max} = 1000$ Hz are the lower and upper boundary of the resonant frequency.
Model of ERS to estimate volume of compound and area of open surface used in optimization
Maintenance requirements

Wear of rails defines to a large extent the maintenance costs of a track structure. Likewise, wear of wheels defines the maintenance costs of a vehicle. Here the wheel-rail wear is estimated by analyzing wheel-rail contact forces. The standard deviation of the contact forces should be minimal in order to reduce the wheel-rail wear. The standard deviation of the wheel-rail contact forces was obtained from the 0.8 sec simulation of the TGV train moving at 90 m/s (324 km/h).
Safety requirements

• Two safety requirements concern the lateral displacements of the rails and strength of the compound. Under a specific angular loading condition, the lateral displacements should not exceed a prescribed limit in order to avoid the gauge from widening and, ultimately, train derailment. Therefore, a special loading case has been considered in which an angular concentrated load has been applied to the rail (at 22 degrees relative to the vertical). For an optimum design, the lateral displacements $u_{x,2}$ and maximum (Von Misses) stress $\sigma_{max}$ should be below their maximum allowable values, i.e.

$$U_{x,2} \leq U_{x,allow} \text{ and } \sigma_{max} \leq \sigma_{allow}$$
• Another requirement concerns upward buckling of a rail. This can happen if there is no (or not sufficient) adhesion between the rail and compound. The vertical (upward) stiffness is then reduced significantly and only depends on the shape of the rail. For a safe design of ERS, the minimum buckling load should not be lower than the prescribed value $P^*_{\text{bckl}}$:

$$P_{\text{bckl}} \geq P^*_{\text{bckl}}$$
Here the minimum allowable buckling force $P_{bckl}^* = 1\text{MN}$ has been used that corresponds to a situation in which very high normal forces in rails are caused by temperature variation and train braking. The buckling force $P_{bckl}$ can be estimated analytically by modeling ERS as a beam on an elastic foundation and using the energy approach that reads

$$P_{bckl} = 2\sqrt{EI K_{up}}$$
• where $EI$ is the flexure of the rail and $K_{up}$ is the upward stiffness of ERS per unit length. To estimate the upward stiffness of ERS, the model has been adjusted so that the rail and compound have no common nodes and there is no friction between the rail and compound. The vertical displacements of the rail are obtained by applying the vertical upward load $F_{y,3}$ and performing the non-linear contact analysis. The vertical displacement of the rail $u_{y,3}$ is then used for the stiffness evaluation as $K_{up} = F_{y,3} / u_{y,3}$. For details on the model data used for the static and dynamic analyses.
• In order to achieve an optimum design of ERS, the cost, acoustic noise, and maintenance (wheel-rail wear) effort should be minimal. Therefore, the corresponding response quantities of ERS, such as the amount of compound, area of open surface, resonant frequency, and contact forces respectively, are i.e.

\[ F_C \equiv V \rightarrow \text{min}, \quad F_N \rightarrow \text{min}, \quad F_M = W \rightarrow \text{min} \]
The requirements that prevent damaging of ERS, train derailment, and buckling of rails have been used as the constraints:

\[
F_1(x) \equiv \frac{u_{x,2}}{u_{x,allow}} \leq 1, \quad F_2(x) \equiv \frac{\sigma}{\sigma_{allow}} \leq 1, \quad F_3(x) \equiv \frac{P_{bckl}^*}{P_{bckl}} \leq 1
\]
Thus, the optimization problem has three objectives. Such problems are characterized by an objective conflict, i.e. when the values of one objective are improved at least one other objective deteriorates. Regarding this problem an improvement of the acoustic properties can be achieved by stiffening the compound, thereby increasing the resonant frequency of ERS. On the other hand, the stiffer the compound the higher the wheel-rail contact forces. And this would entail that the maintenance characteristics of ERS become worse.
A typical approach to solving a multi-objective problem is to convert it to a single objective one. One way to do this is by considering the most important function as the only objective and imposing limits on the other objective functions (treat them as the constraints). The other way is to make a composition of the objective functions while assigning weights (preferences) that reflect the relative importance of objectives for each function. A solution to a composition problem is a compromise solution since it depends on weight factors. An entire set of compromised solutions is called the Pareto set. In practice, a representative subset of the Pareto set is to be determined so that the person in charge (a decision maker) can choose the most appropriate solution.
• The latter approach has been used here to solve the optimization problem. Thus, the following objective function has been constructed:

\[ F_0 = \left\{ w_C \frac{F_C}{F_{C,ut}} + W_N \frac{F_N}{F_{N,ut}} + W_M \frac{F_M}{F_{M,ut}} \right\} \rightarrow \min \]
In which the weight coefficients $w_C, w_N, w_M$ are the preference factors ($w_C + w_N + w_M = 1$) that reflect the relative importance of compound, noise, and maintenance reduction in the final design of ERS. $F_{c, ut}', F_{n, ut}', F_{m, ut}'$, are the normalizing coefficients since the objective functions have different units.
Remarks and conclusions

• The MARS method has been applied to the optimal design of an Embedded Rail Structure. The optimization criteria are formulated using the requirements relating to cost efficiency and safety of railway tracks, minimum noise emission, and minimum wear of wheels and rails. Both the static and dynamic behavior of ERS has been analyzed using finite element numerical models.
The multi-objective optimization problem was solved by transforming it into a single objective problem which had been composed from the original single criterion problems using the preference factor approach. The preference factors representing the relative importance of each objective function during the optimization process can reflect different points of view on optimum design (point of view of society, investor, maintenance contractor, etc.).
• To prevent numerical difficulties, the value of the objective functions were normalized using the results of the single optimizations (utopian solutions) that were performed beforehand.
• To demonstrate the efficiency of the presented procedure, several optimal designs of ERS were obtained using different sets of the preference coefficients. Other designs can be obtained by performing the optimization with different preferences for the optimum design. This can help to make a decision on a final design of ERS.
Coenraad Esveld: Modern Railway Track
Second Edition
MRT-Productions, 2001, Zaltbommel