TEST METHOD TO ASSESS MEMBRANE LAYERS FATIGUE RESPONSE ON ORTHOTROPIC STEEL BRIDGE DECKS

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ABSTRACT
In order to adequately characterize the fatigue response of the various membranes with surrounding multilayer surfacing layers on orthotropic steel decks and collect the necessary parameters for FE modeling, the details of the cyclic Membrane Adhesion Tester (MAT) are introduced. The fatigue damage in membrane interface is related to the amount of dissipated work computed by using the measurement of actuator load and piston deformation during the loading cycle. The dissipated work, which is equivalent to the lost part of the total potential energy of the membrane, has been utilized to explain the incremental damage during the testing. Furthermore, using the experimental data obtained from MAT, ranking of the bonding characteristics of various membrane products is demonstrated as well as the role of other influencing factors, such as the types of substrate and test temperatures.

Keywords: membrane; orthotropic steel deck bridge; fatigue; dissipated energy; adhesive bonding strength

INTRODUCTION
Orthotropic steel deck bridges (OSDB) are widely used in most of the major long span bridges around the world. The lightweight and flexibility make OSDB a cost-effective solution for cases where a high degree of pre-fabrication or rapid erection is required [1] in seismic zones, for movable bridges, long-span bridges and for rehabilitation to reduce bridge weight [2].

An OSDB consists of a deck plate supported in two mutually perpendicular directions by a system of longitudinal stiffeners and transverse crossbeams. Usually, the deck plate is surfaced by bituminous wearing courses. In the Netherlands, an asphaltic surfacing structure for OSDB mostly consists of two structural layers. The upper layer consists of porous asphalt (PA) because of reasons related to noise hindrance. For the lower layer, a choice between mastic asphalt (MA), or guss asphalt (GA), can be made [3]. Two layers of membrane are required to bond the two aforementioned structural layers. Earlier investigations have shown that the bonding strength of membrane layers to the surrounding materials has a strong influence on the structural response of OSDB [4]. The most important requirement for the application of membrane materials is that the membrane adhesive layer shall be able to provide sufficient bonding to the surrounding materials.

In order to adequately characterize the adhesive bonding strength of membranes with surrounding materials on orthotropic steel bridge decks, a Membrane Adhesion Tester (MAT) device has been developed by Delft University of Technology and published in the 92nd TRB annual meeting [4] and in the technical report of this project [5]. A total of eight types of membrane products, representing the most commonly used for waterproofing in OSDB constructions, have been tested under monotonic static loading conditions on different substrates.

The monotonic MAT tests provided a fundamentally sound, mechanistic methodology for the expedient ranking of the bonding characteristics of membrane products. In the second phase of this project, the MAT device was modified to enable the investigation of the fatigue response of the three top ranked membrane products under cyclic loading conditions at different temperatures.

In this paper, the cyclic MAT tests are presented. The characteristics of the tested membrane are briefly introduced. The concept of “dissipated energy” and its utilization for quantification of the damage induced in the membrane due to cyclic MAT loading are discussed.

In the last part of this paper, experimental results of the selected membrane products on various substrates tested at two different temperature conditions (10°C and 30°C) and three different cyclic loading levels (150N, 250N and 350N) are presented. The values of dissipated work for each membrane interface are compared, as well as the relationship between the membrane debonding length and the number of load cycle.

LIST OF MEMBRANE PRODUCTS AND THEIR MECHANICAL PROPERTIES
Product A1 and A2 are waterproof membranes manufactured with SBS(styrene butadiene styrene) elastomeric bitumen and internally reinforced with a non-woven polyester textile. These two products
are installed on concrete decks, steel decks, sand asphalt or asphalt concrete. Product A1 is applied on
the steel plate, while product A2 is applied on the Guss asphalt.

Product A1 and A2 can be bonded to the prepared substrate by melting the film on the
membrane surface and softening of the bitumen. Details of the product specifications can be seen in
Table 1.

Table 1 Specifications of product A1 and A2 from company A

<table>
<thead>
<tr>
<th>Test and specification</th>
<th>Units</th>
<th>Standard</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nominal values</td>
<td>Critical values</td>
</tr>
<tr>
<td>Main surface thickness</td>
<td>mm</td>
<td>EN 1849-1</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.8</td>
<td>4.6</td>
</tr>
<tr>
<td>Tensile strength at break (20°C,100mm/min)</td>
<td>N/5cm</td>
<td>EN 12311-1</td>
<td>950</td>
<td>820</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>950</td>
<td>820</td>
</tr>
<tr>
<td>Elongation at break (20°C, 100mm/min)</td>
<td>%</td>
<td>EN 12311-1</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>

There are two types of membranes from company C. Product C1 is used only as a bottom
membrane, whilst product C2 can be used both as top and bottom membranes in asphalt surfacing
systems on steel bridge decks.

Product C1 is a 2.4 mm thick single- ply membrane, with non- woven polyester fleece. This
product is used for the single- ply sealing under stone mastic asphalt, mastic asphalt or bituminous
concrete.

Product C2 is a 4.7 mm thick single- ply membrane, with 1.5 mm strong fleece. This
membrane is provided with a modified bituminous mass of 1.6 mm thickness on both sides. Product
C2 is a waterproof membrane for bridges, and provides high resistance to traffic loading. The details
of specifications for products C1 and C2 are shown in Table 2.

Table 2. Specifications of products C1 and C2 from Company C

<table>
<thead>
<tr>
<th>Test and specification</th>
<th>Units</th>
<th>Standard</th>
<th>C1</th>
<th>C2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>EN 1859-2</td>
<td>2.4</td>
<td>4.7</td>
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<tr>
<td>Tensile strength MD/TD</td>
<td>N/50 mm</td>
<td>1350/1150</td>
<td>1350/1150</td>
<td></td>
</tr>
<tr>
<td>Elongation at tensile strength MD/TD</td>
<td>%</td>
<td>ISO 527</td>
<td>50/70</td>
<td>50/70</td>
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</tbody>
</table>

EXPERIMENTAL SETUP AND TEST CONDITIONS

The membrane fatigue tests were performed at two temperatures (10°C and 30°C). The fatigue
tests at 10°C, were performed with a sinusoidal loading F ranging between $F_{\text{min}} = 50 \text{N}$ and $F_{\text{max}} = 150 \text{N}$ at a frequency of 5 Hz for 432 000 cycles. $F_{\text{max}}$ was increasing every 432 000 cycles, starting
from 150N, then 250N and finally, 350N, see Figure 1.
For the fatigue tests at 30°C, the sinusoidal loading $F$ varied from $F_{\text{min}} = 50\text{N}$ to $F_{\text{max}} = 100\text{N}$ at a frequency of 5 Hz. The number of applied load cycles was 864 000.

In order to run the tests under temperature controlled conditions the set up needed to be properly insulated. For this project, a climate chamber was used to enable testing under different temperatures.

The MAT setup is capable of operating in both a monotonic or a cyclic mode. For cyclic tests, the maximum allowed load is 500N. The frequency range is $1 - 5$ Hz and the maximum allowed displacement from the bottom position is 150mm. The schematic diagram of MAT setup is shown in Figure 2.
In the Netherlands an asphaltic surfacing structure for orthotropic steel bridge decks mostly consists of multilayers, see Figure 3. The upper layer consists of Porous Asphalt (PA) for noise reduction. For the lower layer a choice between Mastic Asphalt (MA) or Guss Asphalt (GA), can be made. One membrane layer is utilized to bond the surfacing layers together and an other one to bond the surfacing layer to the steel deck. In order to characterize the interface adhesive bonding strength between various membrane products and the surrounding asphalt and steel material layer, four types of specimen, i.e. steel-membrane specimen (SM1), Guss Asphalt concrete-membrane specimen (GM1 and GM2) and Porous Asphalt-membrane specimen (PM2) were tested. The GM system consists of two interfaces, with membrane-1 at the bottom of the Guss Asphalt (GM1) and membrane-2 at the top of the Guss Asphalt (GM2), see Figure 3. Therefore two types of GM specimens have been investigated.

![FIGURE 3 Schematic of a typical Dutch asphalt surfacing system on a steel bridge deck](image)

Figure 3 and Table 3 illustrate the combinations of membrane materials and surfacing layers tested in this research. Products A1 and C1 have been tested only at SM1 and GM1 interfaces, product A2 only at GM2 and PM2 interfaces while C2 product in all interfaces.

<table>
<thead>
<tr>
<th>Membrane type</th>
<th>A</th>
<th>A2</th>
<th>C1</th>
<th>C2</th>
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<tbody>
<tr>
<td>SM1</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>GM1</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GM2</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>PM2</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
DISSIPATED ENERGY APPROACH FOR FATIGUE ANALYSIS OF MAT

Dissipated energy was used as an indicator of damage in asphalt materials [6],[7]. These researchers postulated that the fatigue life depends on the accumulation of dissipated energy from each load cycle. In later studies, damage was related to the rate of change in dissipated energy from one cycle to the next [8].

In this study, the dissipated energy concept has been utilized for MAT cyclic loading tests to characterize the fatigue life of membrane products bonded on the different substrates at different temperatures and loading levels. The fatigue damage in the interface between membrane and substrate is related to the amount of dissipated work computed by using the measurement of the actuator load and the membrane deformation during each loading cycle. The dissipated work per loading cycle, which is equivalent to the lost part of the total potential energy supplied to the membrane by the actuator per cycle, was used in this study as a measure of the incremental damage in the interface between the membrane and substrate during the testing.

Dissipated Energy Concept

Applying a load to a material, the area under the stress-strain curve represents the energy being input into the material. During the loading-unloading process, if the unloading curves do not coincide with the loading but trace different paths, an energy loss is occurred within the material. Part of the energy is dissipated out of the material system due to the external work, in the form of mechanical work, heat generation, or damage.

The dissipated energy from cycle loading can be determined by calculating the energy losses associated with the phase angle, see Figure 4 (a). The area of the hysteresis loop in Figure 4(b) represents the dissipated energy and the following equations can be used to calculate its value in a linear viscoelastic material.

where

\[ \text{DE}_i = \pi \sigma_i \varepsilon_i \sin \phi_i \]  

(1)

\[ \text{DW}_i = \pi F_i \delta_i \sin \phi_i \]  

(2)

where

- \text{DE}_i = \text{dissipated energy in cycle } i;
- \sigma_i = \text{stress level in cycle } i;
- \varepsilon_i = \text{strain level in cycle } i;
- \phi_i = \text{phase angle between } \sigma \text{ and } \varepsilon \text{ in cycle } i;

When stress \( \sigma \) is not a directly measurable quantity, the above equation can be expressed in terms of dissipated work as:
\[ F_i = \text{force level in cycle } i; \]
\[ \delta_i = \text{displacement level in cycle } i; \]
\[ \phi_i = \text{phase angle between } F \text{ and } \delta \text{ in cycle } i; \]

The relative change in the amount of the energy dissipated is directly related to damage accumulation. A low amount of relative change in energy dissipation can be found either in high fatigue resistance materials, low external loading amplitudes, or both. Such relative change in dissipated energy represents the total effect of fatigue damage without the necessity of considering material type, loading modes and severity separately.\(^9\).

This concept was first initiated by \(^8\) who suggested using the change in dissipated energy to relate damage accumulation and fatigue life. The work was refined and expanded by \(^10\), and then well applied and verified by \(^11\) who used the ratio of dissipated energy change (RDEC) as an energy parameter to describe HMA (Hot Mix Asphalt) fatigue damage. This ratio can be represented as:

\[
\text{RDEC}_a = \frac{\text{DE}_a - \text{DE}_b}{\text{DE}_a (b-a)} \quad (3)
\]

where

\[
\text{RDEC}_a = \text{the average ratio of dissipated work change at load cycle } a, \text{ comparing to next cycle } b;
\]
\[ a, b = \text{load cycle } a \text{ and } b. \text{ the typical cycle count between cycle } a \text{ and } b \text{ is 100, i.e., } b-a=100; \]
\[ \text{DE}_a, \text{DE}_b = \text{the dissipated work produced in load cycle } a \text{ and } b \text{ respectively}; \]

Similar as Eq. (3), Eq. (4) can be expressed by using the ratio of dissipated work change (RDWC) as:

\[
\text{RDWC}_a = \frac{\text{DW}_a - \text{DW}_b}{\text{DW}_a (b-a)} \quad (4)
\]

where

\[
\text{RDWC}_a = \text{the average ratio of dissipated work change at load cycle } a, \text{ comparing to next cycle } b;
\]
\[ a, b = \text{load cycle } a \text{ and } b. \text{ the typical cycle count between cycle } a \text{ and } b \text{ is 100, i.e., } b-a=100; \]
\[ \text{DW}_a, \text{DW}_b = \text{the dissipated work produced in load cycle } a \text{ and } b \text{ respectively}; \]

RDEC or RDWC eliminates the energy that is dissipate in other forms without producing damage. This provides a true indication of the damage being done to the mixture from one cycle to another by comparing the previous cycle’s energy level and determining how much of it caused damage.

As introduced by \(^11\-13\) the damage curve represented by RDEC vs. loading cycles shows three stages: a rapid decrease, followed by a plateau stage (stage II) for the majority of the fatigue cycles. The plateau stage (stage II), an indication of a period where there is a relatively constant percentage of input energy being turned into damage, will extend throughout the main service life until a dramatic increase in RDEC, which gives a sign of true fatigue failure (stage III). The schematic chart is given in Figure 5.
EXPERIMENTAL RESULTS

The first group of tests was conducted at three load levels (150N, 250N, 350N) at 10°C. The results are presented below for all products (A1, A2, C1 and C2) and all interfaces (SM1, GM1, GM2, PM2).

Figure 6 shows the ratio of dissipated work change (RDWC) curves for three different membrane products at three different load levels (150N, 250N and 350N) at 10°C. Figure 7 shows the dissipated work and the membrane debonding length for three different membrane products versus the number of load cycles. The comparisons have been conducted for all products at the steel/membrane (SM1) interface.

In Figure 6 it can be observed that, after the initial loading period, the plateau stage was reached. At the SM1 interface, the plateau values of product C1 were always lower than the other two products indicating that less input energy turned into SM1 interface damage. Particularly, at 150N and 250N load levels, almost no energy was turned into fatigue damage for product C1.

Product C2 was found to have better fatigue resistance than product A1 at 150N and 250N load levels. However, at 350N load level product A1 was found to have lower RDWC values than...
product C2. That can explain why at 350N load level, membrane C2 was debonded earlier than product A1, see Figure 7.

FIGURE 7. Dissipated work and debonding length of steel/membrane interface 1 (SM1)
In Figure 8, the results for product A1, C1 and C2 at GM1 interface are presented. Similarly as in SM1 interface, product C1 was found to have the lower RDWC values followed by product C2 and A1 respectively. At 250N load level, the RDWC curves for product C2 and C1 overlapped showing a similar response at GM1 interface. Product A1 could not be tested at 350N load level because it was fully debonded during the first 100,000 cycles of the 250N load level.

At the GM2 interface, only products A2 and C2 were tested. These products were fully debonded at 250N load level, hence only the RDWC curves of 150N and 250N are presented in...
Figure 9. Although slightly lower RDWC values occur for product C2 at 150N load level, it can be observed that both products demonstrated a similar response. At the 250N load level, RDWC values are higher for product A2 than for product C2 proving that product C2 had better fatigue resistance at GM2 interface than product A2.

**FIGURE 10. Ratio of dissipated work change of Porous AC/membrane interface 2 (PM2)**

At the PM2 interface, product C2 was found to have slightly lower values of RDWC at 150N load level (Figure 10). However, a significant difference of RDWC between those two products can be observed at 250N load level. It can also be seen that the RDWC curve of product A2 stopped developing after 200,000 load cycles because it was fully debonded.

The results from the tests conducted at 30°C are presented below. These tests were performed at one load level, 100N for 864,000 cycles for all products and interfaces. Nevertheless, at some interfaces the tests were completed before the maximum of 864000 load cycles due to large deformation of the samples.
Figure 11 shows the results for products A1, A2, C1 and C2 at the SM1, GM1, GM2 and PM2 interfaces. For product A1 at the SM1 and the GM1 interfaces, the SM1 interface was found to be the one with the lower values in terms of dissipated work producing a steady response throughout the fatigue test. At the GM1 interface, the debonding process started since the beginning of the test resulting to full debonding after the first 100,000 loading cycles while the calculated dissipated work was also found to increase since the beginning of the test.

For product A2, the GM2 interface is better than PM2 in terms of dissipated work. High rate of debonding was observed at PM2 interface at 100,000 cycles.

The results of product C1 are also presented in Figure 11. This product is used only as a bottom membrane which means that is only applicable on steel plate and Guss asphalt. SM1 interface was found to be the one with the lower values in terms of dissipated energy therefore producing a steady response throughout the fatigue test. It can be noticed that the SM1 interface has zero debonding. On the other hand, GM1 was found to have 45mm of debonding length at the end of the test.

For product C2, it can observed that SM1 interface is the worst one in relation to the membrane debonding speed. GM1 and GM2 interfaces demonstrate almost the same response.
In Figure 12 the RDWC of three different products, tested at a temperature of 30°C and a load level of 100N, is compared. For both SM1 and GM1 interfaces at 30°C, product C1 was found to have lower RDWC values than product A1 and C2. At GM1 interface, products C2 and A1 were found to have similar response with the RDWC curves overlapping. However, a significant difference can be observed at the SM1 interface between products C2 and A1; higher RDWC values occurred for product A1 at the SM1 interface.

At the GM2 interface, product A2 was found to have lower RDWC values than product C2 while at the PM2 interface, product C2 was found to have lower RDWC values. Finally, it can be seen that product C2 at PM2 interface reached its plateau stage earlier than product A2.

CONCLUSIONS

Based on the presented results, the following conclusions can be made:

- The MAT set up is capable of characterizing the fatigue response of the various membranes bonded on the different substrates. The test results allow a better understanding of the membrane performance on the bridge structure allowing thus optimization of maintenance activities;
- The fatigue response of a membrane product is influenced not only by the surrounding substrate but also by the environmental temperature and loading level applied on the membrane;
- The concept of dissipated energy/work provides a fundamental and expedient means to evaluate the fatigue life of membrane products on different substrates;
- Product C1 performs quite well as the bottom membrane, both at 10°C and 30°C, in term of values of dissipated work and debonding length.
- Product C2 and A2 are considered as the best choices for the top membranes.
- The observations from the MAT cyclic loading tests are coincident to the observations from MAT monotonic static loading tests in the previous paper. It means that the findings of this study is a further proof that the methodology utilized in this research project is adequate for ranking the bonding characteristics of various membrane products on different substrates for OSDB construction.
ACKNOWLEDGEMENTS:

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