Extending the Service Life of Civil Structures

Towards a Shared Innovation Programme

Based on the Workshop held in Amsterdam, the Netherlands
27 November 2014

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Colophon
This publication is partly based on the proceedings of the workshop 'Extending the Service Life of Civil Structures', an initiative of TNO.

Reference is made to several presentations. If you are interested in these, or would like further information, please contact Arie Bleijenberg via arie.bleijenberg@tno.nl or Jeroen Kruithof via jeroen.kruithof@tno.nl.

TNO.NL/ASSETMANAGEMENT

Acknowledgements

On 27 November 2014, experts from seven European countries, representing twenty organisations, gathered in Amsterdam, at the workshop 'Extending the Service Life of Civil Structures'. Thirty participants contributed to discussions on major challenges for ageing civil structures in Europe, and joined forces to define the most promising innovation routes for extending the service life of the structures.

First of all, I would like to thank all participants (see next page) for attending this inspiring event and contributing their experience, expertise and vision to formulate a shared vision on extending the service life of civil structures.

This would not have been possible without the thoughtful presentations given by:

- Prof. Werner Rothengatter (Karlsruhe Institute of Technology and advisor to the Pällmann Commission and Daehre Commission) – Future of transport infrastructure financing
- David Ashurst CEng MICE (Associate Director of ARUP)
- Frank van Dooren MSc (Rijkswaterstaat)
- Heinz Friedrich Dipl.-Ing. (BASt)
- Prof. Robby Caspeele (Ghent University)
- Prof. Max Hendriks (Norwegian University of Science and Technology)
- Peter Tanner, Civil Eng. (Eduardo Torroja Institute for Construction Science – Spanish National Research Council and CESMA Ingenieros)
- Dr Claus K. Larsen (Norwegian Public Road Administration)

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Delft, 30 January 2015

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1 Most promising routes for innovation

1.1 Extending the service life of civil structures

Throughout Europe, structures such as bridges and viaducts are approaching the end of their service life. Material degradation is a direct consequence of ageing and leads to reduced resistance to environmental impacts. In the meantime, some of these environmental impacts, or loads for short, have increased. Traffic loads and extreme weather conditions such as wind loads or wave loads are not as predicted in the 1960s or 1970s when a significant proportion of the existing infrastructure was designed. As a result, the safety of structures is a matter for concern and in several European countries they will eventually have to be renovated or replaced. However, replacement and renovation are costly, and cause inconvenience to users.

During the workshop we saw examples from:

- Germany, where the Daehre Commission determined a € 7.2 billion annual re-investment need (for all transport infrastructure) [A2] and an annual maintenance backlog of € 2.65 billion.
- Norway, which has an annual maintenance backlog of € 0.5 - 1 billion [B4]
- The Netherlands, with an expected annual reinvestment need for civil structures of € 0.2 - € 0.5 billion [A1].

In the coming decades, extending the service life of civil structures will be the major challenge in attempts to cut maintenance costs and reduce nuisance for road users all over Europe. In order to initiate the development of a joint research agenda at European level, TNO organised a European workshop, which was held on 27 November 2014. More than thirty experts from twenty European organisations in seven European countries jointly formulated answers to the following questions:

- What are the most promising routes for extending the service life of civil structures?
- What are the technologies/innovations needed in order to put them into practice?

The most promising routes have been formulated separately for concrete and steel structures.

1.2 Ageing concrete structures

Twenty participants from various fields (academia, engineering offices and governmental engineering offices) contributed to this session, providing a broad scope for formulating problems as well as defining routes for innovation. The topics covered focused both on concrete assets in particular and ageing civil structures in general (see also Figure 1).

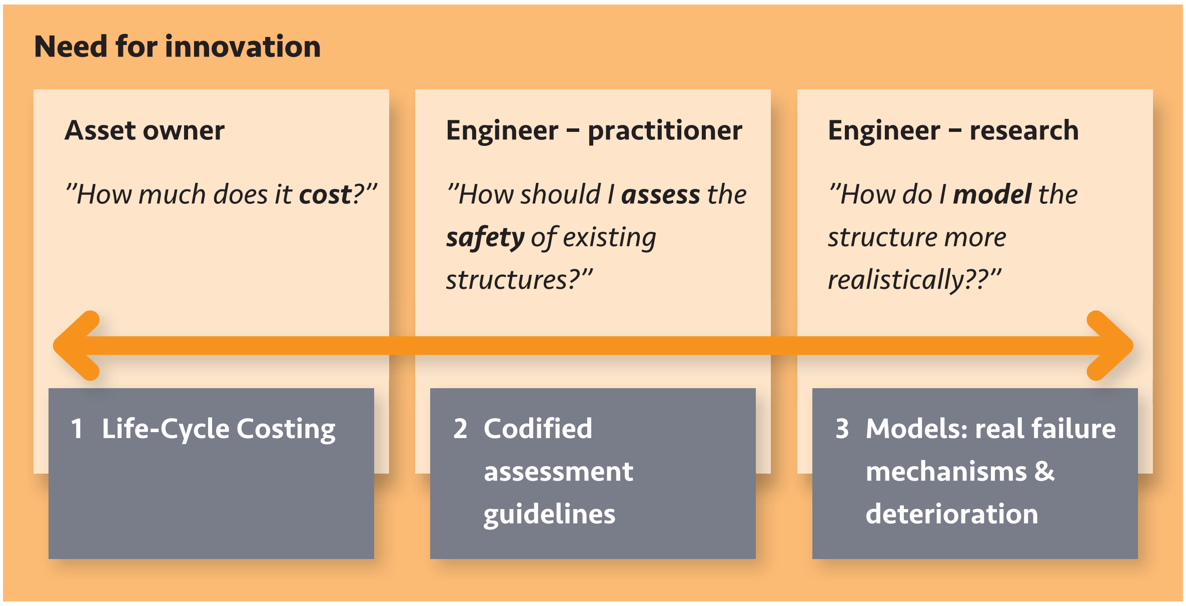

Figure 1. Promising routes to innovation for ageing concrete civil structures

1 Life-Cycle Costing methodology

From the point of view of the asset owner, technical problems and solutions should be translated into life-cycle costs. There is a need for quantitative, preferably monetised decision support for the management and maintenance of existing infrastructure.

a. Development of an applicable framework for Life-Cycle Costing (LCC).
b. Determining the time-dependent behaviour of various maintenance measures and their cost aspects.
c. Development of a decision-support tool.
d. Extension of costing methodology to environmental effects.

2 Developing practical codified assessment guidelines for existing structures

In order to assess and continuously guarantee the safety and availability of civil structure assets, practitioners require a framework, ultimately in the form of a norm, to deal with assessment and evaluation, as well as interventions.

a. Determine guidelines on what to measure and monitor and how.
b. Determine methods for incorporating qualitative information in a quantitative way.
c. Determine how to use the information gathered to update load parameters, resistance parameters and partial factors in day-to-day engineering.
d. Develop practical models for resistance of existing structures.
e. Develop suitable reliability levels based on cost optimisation and human safety requirements.

3 **Advanced models of structures**

3.1 Modelling real failure mechanisms, avoiding hidden safeties in structural models

There is a knowledge gap in the field of the behaviour of structures as a system, and the impact of this behaviour on overall structural reliability.

a. How to define and assess system reliability, for ductile or brittle behaviour.
   - What is the effect of local behaviour on global structural reliability?
   - Develop different acceptance criteria and safety format for system and section levels.
   - Develop load models for system and section levels.
   - Develop a common rationale for assessing the robustness of existing structures.

b. Perform large-scale tests to calibrate the models, also for dynamic loadings.

c. Methods and requirements for non-destructive testing, in order to determine properties.

d. Better understanding of soil-structure interaction.

e. Development of Non-Linear Finite Element Modelling (NLFEM) for existing structures for different failure mechanics.

f. Development of a safety format for NLFEM calculations.

g. How to assess model uncertainties.

3.2 Developing alternative structural models for deteriorating structures

The resistance of an ageing structure is dependent on the condition of the materials of which it is composed, for example the level of degradation of reinforcement bars. However, there is limited knowledge on how and in what form to include material degradation in structural models.

a. Develop probabilistic models for local and global deterioration.

b. Perform small- and large-scale experiments on deteriorating structural elements.

c. Couple deterioration to reliability assessment over a certain (remaining) lifetime.

1.3 Ageing steel structures

During the working session on steel structures, the European experts decided on the most promising routes for extending the service life of steel bridges. The routes are shown in Figure 2. What is necessary for both routes is a **decision-making tool for assessing existing bridges** which will be useful for the process of selecting the bridges for re-assessment and deciding whether to do nothing, to renovate or to replace. A couple of aspects need to be defined as input for the decision-making tool:

- Knowing the condition of the assets as precisely as possible.
- Knowing the different options for strengthening the assets.

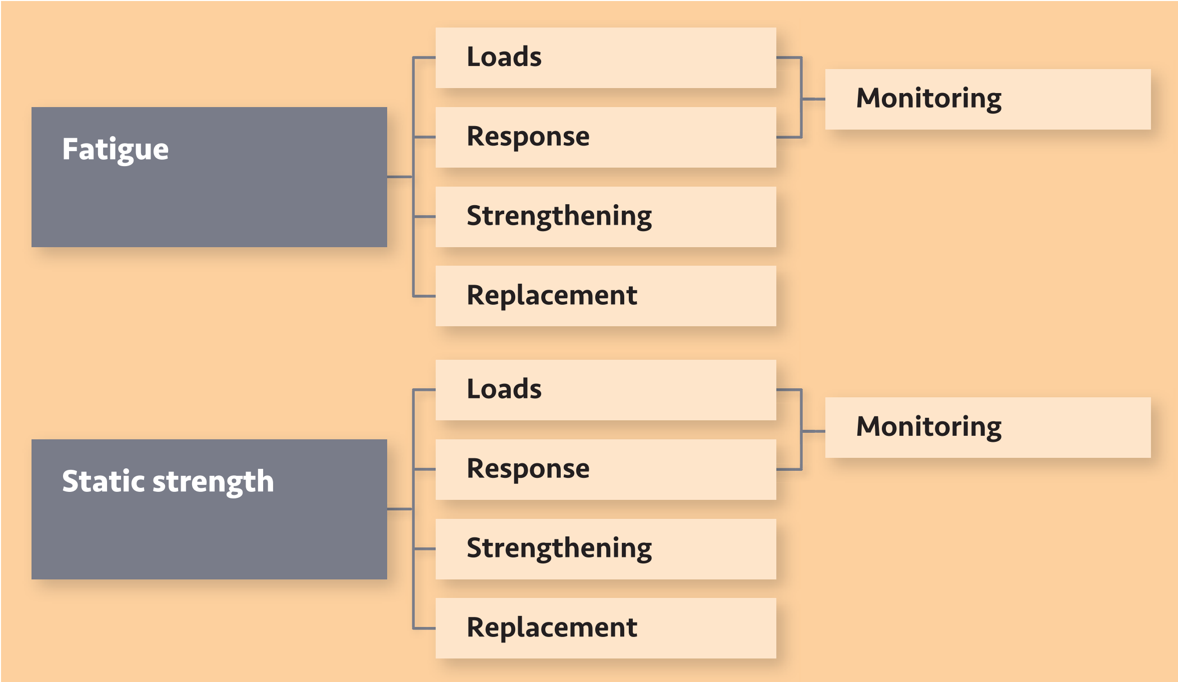

Figure 2. The most promising routes for extending the service life of steel structures

The technologies and innovations needed for the routes set out are described in the following sections.

1. Fatigue strength

1.1 Loads and response (monitoring)

The process of measuring and monitoring the stresses on representative bridges could provide important data that can be used for all the bridges on a highway.

The following technologies are required:

a. Develop accessible, reliable and competitive monitoring systems with a long life.
b. Develop sensor techniques that are able to detect even minor fatigue damage/degradation in the structure and give accurate estimations of the fatigue degradation process (size, position and growth).
c. Methods for automatic and standard data processing (of the data provided by the monitoring systems).
d. Provide better estimations of fatigue loads and update the fatigue load model from Eurocode with the help of measured data.
e. Write a guideline for engineers for extracting the stresses (hot-spot or nominal) for fatigue for use in the design stage of new and existing bridges.
f. Measures to harmonise national standards for existing structures.
g. Improve the partial factors for fatigue given in the standards, for existing structures, for the two cases: with and without monitoring/inspection.

1.2 Strengthening

Regarding the strengthening of steel bridges for fatigue, there are two levels for the proposed innovations and research: a broad level and a more focused one.

For the broader innovations, better exploration of the following aspects is proposed:

a. Create new renovation techniques for steel bridges that use simple and unsophisticated on-site technologies (low-tech on-site) and high-tech solutions in workshops, as opposed to solutions such as a high-strength concrete overlay poured on site.
b. Find new ways to strengthen movable bridges.
c. Look into strengthening and renovation techniques for the main girder system.

On a more focused level, the following innovations are needed:

a. Find and qualify the life enhancement of post-weld treatments on existing structures and determine the boundaries of application
b. Find new welding techniques for 'old steels'
c. Develop 'cold' (i.e. non-weld) repair techniques for short, medium and long-term structured life extension.
d. Find repair techniques that can be carried out with ongoing traffic.

1.3 Replacement

Regarding the option of replacing ageing structures, there are plenty of lessons to be learned for new bridges regarding not only the technical aspects but also by planning for monitoring and inspection.

Research into the following aspects is proposed:

a. Develop bridge-renewal techniques with faster construction.
b. Develop bridge-renewal techniques that can be carried out in extremely limited spaces.
c. Better regulate robustness of designs in standards.

2. Static strength

2.1 Loads and response monitoring

The research topics proposed in this area covered several issues, including:

a. Explore the options and effects of regulations on load limitation and the enforcement of these regulations using monitoring systems.
b. Improve the load models for the Ultimate Limit State (ULS) by using measured traffic load data on bridges (to be generally used and applied in standards).
c. Implement a uniform methodology for extrapolating measured data to target probability levels (for bridge-specific use).

2.2 Strengthening

For strengthening the static capacity of steel bridges, improved methodologies, manuals and better techniques should be looked into. The focus should be on all assets, including smaller bridges.

2.3 Replacement

The robust bridge design for future traffic loads should be regulated in norms (see Route 1 – Fatigue).

1.4 Call for action

Maintaining a reliable and safe (transport) infrastructure network is the concern of every asset owner. During the workshop we saw that the budget required to maintain the current infrastructure network will increase rapidly. The examples from Germany, Norway and the Netherlands are all proof of annual re-investment needs and maintenance backlogs of many billions of euros.

The effectiveness of the replacement programmes is of concern to all citizens, as is the safety of civil structures. We call for **national and European policy-makers** to exert their influence on programmes such as Horizon 2020 and Infravation, to encourage and support the building and sharing of knowledge on extending the service life of civil structures. During the workshop, the main focus points for engineering were identified. It is now time to take action. To reach an optimum in both the short and the long term, knowledge of existing structures has to be developed, existing academic knowledge should be continuously made available to practitioners in codified format and, at the same time, existing and new knowledge on structures should be translated into (life-cycle) cost aspects.

The challenge of dealing with ageing infrastructure cannot be addressed in an effective, efficient and sustainable way on the local and national level alone. We also call upon **European knowledge institutions** to accelerate the building and sharing of a common knowledge base in the field of existing structures. Existing working groups of platforms such as fib (International Federation of Structural Concrete) and RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) provide a framework for working on several of the most urgent topics.

The workshop was a unique event, where experts from all over Europe jointly drafted a research agenda for extending the service life of civil structures. Let us continue to work together, by disseminating this agenda and using it in our own organisations. Together we can change the future by carrying out this joint research agenda to prevent a future with spiralling maintenance costs and considerable nuisance for road users!

2 Introduction

2.1 The Issue

Throughout Europe, structures such as bridges and viaducts are approaching the end of their service life. Material degradation is a direct consequence of ageing and leads to reduced resistance to environmental impacts. In the meantime, some of these environmental impacts , or loads for short, have increased. Traffic loads and extreme weather conditions such as wind loads or wave loads are not as predicted in the 1960s or 1970s, when a significant proportion of the existing infrastructure was designed. As a result, the safety of structures is of concern and in several European countries they will eventually need to be renovated or replaced. However, replacement and renovation are costly, and cause inconvenience to users.

In the coming decades, extending the service life of civil structures will be the major challenge. Innovations which **extend the service life** of civil structures will cut maintenance costs and reduce nuisance for road users all over Europe.

With a view to setting up a joint research agenda at European level, TNO organised an international workshop, which was held on 27 November 2014. Here, more than thirty experts from twenty European organisations in seven European countries jointly formulated answers to the following questions:
- What are the most promising routes for extending the service life of civil structures?
- What are the technologies/innovations needed in order to put them into practice?

2.2 The Process

The purpose of the workshop was to facilitate the process of finding joint answers to these questions. The schedule can be seen on the following page.

The event began with a plenary session during which, two keynote speakers as well as the host highlighted the urgency of the challenge posed by ageing civil-structure assets.

As from a technical perspective typical steel and concrete structures have different issues, two separate workshops provided a framework for defining the routes and the required innovations. Each workshop began with short presentations by experts in the field, who shared their vision on the most promising routes for service life extension as well as the necessary developments.

The main part of the workshops was dedicated to formulating answers to the questions above. In the steel workshop, a framework for the routes was proposed by the session leader and developed further by the group. In the workshop for concrete structures, four sub-groups discussed and defined innovation routes (three per group). The routes were then further prioritised by the plenary group (and clustered where necessary). In this process the question

'What are the most promising routes for extending the service life of civil structures?' was answered by the plenary group. Then, three main priorities were chosen by the whole group. These were fleshed-out in smaller groups, with the aim of answering the question: 'What are the technologies/innovations needed in order to put them into practice?'

A final plenary session provided an opportunity to present the proposed routes, answer questions and gather feedback.

2.3 Schedule

10.00-10.45	**Welcome**	*Refer to*
10.45-11.00	**Opening**	
	— Arie Bleijenberg MSc, TNO	A-1
11.00-12.30	**Challenges of ageing European infrastructure**	
	— Prof. Werner Rothengatter – KIT; advisor to the Pällmann Commission and Daehre Commission (Future of transport infrastructure financing)	A-2
	— David Ashurst CEng MICE – Associate Director, ARUP	A-3
12.30-13.30	**Lunch**	
13.30-16.30	**Workshops on ageing structures**	
	Concrete structures	
	Led by Prof. Raphaël Steenbergen (TNO)	
	— Prof. Robby Caspeele (Ghent University): Safety of existing structures: linking theory and practice	B-1
	— Prof. Max Hendriks (Norwegian University of Science and Technology): Future in FEM for concrete structures	B-2
	— Peter Tanner, Civil Eng. (IETcc-CSIC and CESMA Ingenieros): Innovative methods for the preservation and retrofitting of existing structures	B-3
	— Dr Claus K. Larsen (Norwegian Public Road Administration): Present and future challenges of ageing concrete infrastructure in Norway	B-4
	Steel structures	
	Led by Prof. Johan Maljaars (TNO)	
	— Frank van Dooren MSc (Rijkswaterstaat): Experience and future challenges with existing steel civil structures in the Netherlands	C-1
	— Heinz Friedrich Dipl.-Ing. (BASt): Practical experience, solutions and research into steel bridges in Germany	C-2
16.30-17.00	**Conclusions – Sharing and feedback**	
17.00-18.00	**Reception**	

The following sections summarise the content of the event. The presentations can be found in the Appendix.

3 Challenges of ageing European transport infrastructure

Guaranteeing the availability and safety of a constantly ageing aging areal of civil structures is more than a local or national problem. This was illustrated with examples from several countries, presented by the host of the event and two keynote speakers.

Arie Bleijenberg MSc (TNO) gave an overview of the situation regarding ageing infrastructure in **the Netherlands**. [A1] A significant increase in the number of constructions to be refurbished is necessary in the coming decades, implying costs of at least € 150 million, up to € 500 million on a yearly basis. Increasing the service life of existing structures will help to stay close to lower cost margin – saving hundreds of millions of euros in the national budget. As an example, by increasing the mean repair life from 10 to 25 years, the number of necessary bridge replacements decreases by approximately 40% in 2020 and by an even higher proportion in the later decades (Figure 3).

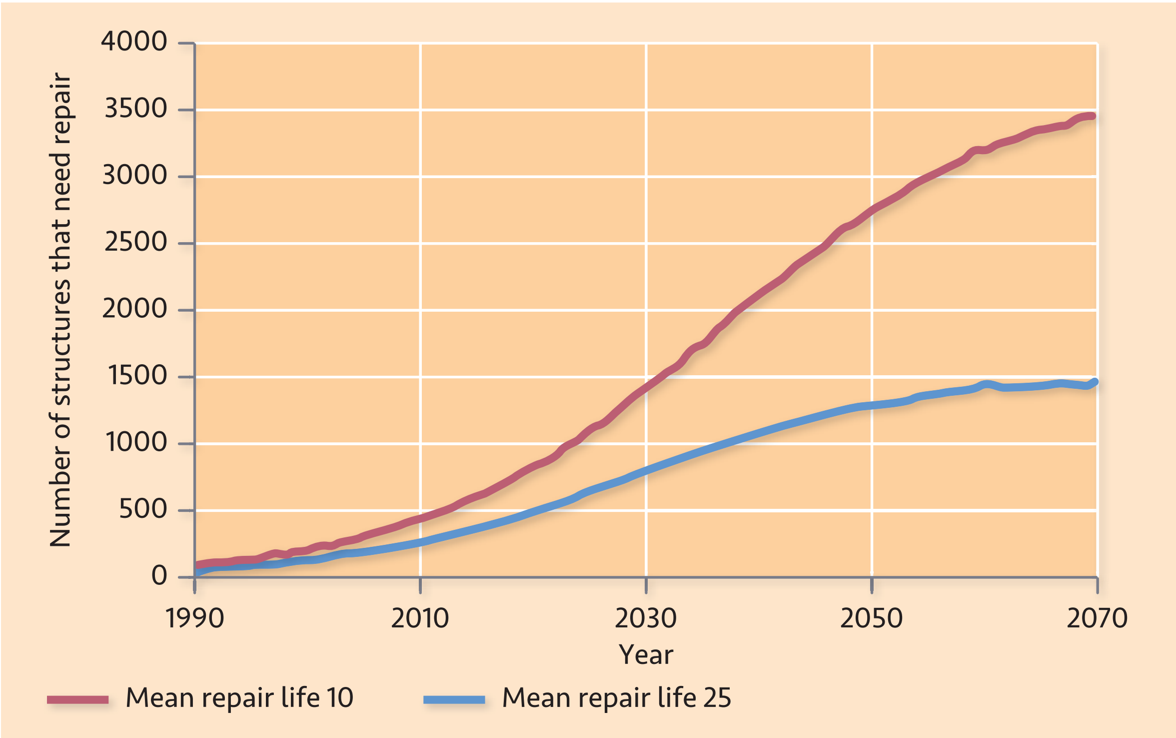

Figure 3. Estimated increase in the number of structures in need of repair on Dutch highways. Source: Non-traditional assessment and maintenance methods for aging concrete structures – technical and non-technical issues; R.B. Polder et al.– Materials and Corrosion 2012, 63, No. 12.

Prof. Werner Rothengatter (Karlsruhe Institute of Technology) addressed the issues mainly on the level of decision-making and planning of infrastructure investment. [A2] In **Germany**, significant efforts have been made to describe the lifetime of civil structures (components) in statistical terms, while these models can be further improved by also taking account of visual inspections and technical depletion.

Besides the physical models however, life-cycle planning should account for financial aspects. Prof. Werner Rothengatter suggests that research in the field of investment theory and operations research is well defined. In the meantime, public budgets do not reflect the needs imposed by the large number of ageing structures, thereby creating a significant maintenance backlog – € 2.65 billion per year in Germany alone (Daehre Commission, 2012). The Pällmann Commission (2000), Daehre Commission (2012) and Bodewig Commission (2013) have worked on advising decision-makers on dealing with existing infrastructure. The inclusion of physical and financial life-cycle planning in new infrastructure projects was one of the key recommendations. This approach can be supported by, among others, BIM modelling of all large infrastructure projects, which has been recommended as a legal requirement to policy-makers in Germany.

In the meantime, at European level, infrastructure investments focus mainly on new construction. If sufficient exploitation or maintenance budgets are not foreseen, this infrastructure will degrade rapidly – for example the high-speed rail network in **Spain**. From this aspect, a positive example of such life-cycle approach to infrastructure investments was the restrictive policy adapted by the **Czech** Transport Master Planning. To strengthen the financial situation of public works Prof. Rothengatter advocated for inclusion of privately managed organisations and trust funds. David Ashurst CEng MICE, the second key-note speaker, addressed the situation in the **United Kingdom**. [A3] In the coming five years, the largest-ever infrastructure investments are planned for roads and railways, amounting to € 80 billion. Rothengatter pointed out the needs of infrastructure asset owners: safety, adapting to future requirements, optimising the use of existing assets, understanding deterioration and minimising disruption to operation. In the meantime, technical challenges have to be addressed, including: fatigue problems, accurate inspection and monitoring techniques, chloride damage, ageing of post-tensioned concrete bridges. According to Mr Ashurst CEng MICE, the focus points of ageing structures are: (1) Getting to know assets, (2) Fatigue in steel structures, and (3) Chloride ingress. The presentations indicate not only that the ageing of the existing civil structures is a Europe-wide issue, but also that the challenges are found in a broad range of fields, from specific technical questions to investment models and policymaking. The discussions that followed focused on technical aspects, and partly addressed life-cycle costing.

4 Concrete structures

The parallel session about ageing concrete structures was led by Prof. Raphaël Steenbergen (TNO).
Twenty participants from various fields (academia, engineering offices, governmental engineering offices) contributed to the work of this session, providing a broad scope for formulating problems as well as defining routes for innovation.
The presentations and discussions are summarised in the following sections.

4.1 The experts' viewpoint: challenges and visions

4.1.1 Safety of existing structures: linking theory and practice

Prof. Robby Caspeele (Ghent University) proposed six main challenges as promising routes for development:

- Developing practical codified assessment guidelines for existing structures, based on a probabilistic approach and applicable for practical use by introduced safety factors.
- The guidelines should be compatible with the Eurocode framework and able to account for alternative safety levels, remaining working life, reference period and additional information.
- Taking account of real failure mechanisms, spatial variability including (time-dependent) degradation and system behaviour when quantifying structural reliability.
- Developing a common rationale for robustness assessment of existing structures.
- How to incorporate qualitative information from inspections in a quantitative way.
- Quantifying the influence of different assessment methods on the structural reliability level.
- Dealing with the increased complexity in the assessment of existing structures. 'Beyond failure probability' (P_f) take the cost aspect of risk into account in decision-making (in a more advanced way than is currently the case).

4.1.2 Future in FEM for concrete structures

Prof. Max Hendriks (Norwegian University of Science and Technology & Technical University of Delft) focused on Non-Linear Finite Element Modelling (NLFEM). NLFEM is a resource-intensive computational method that describes structural behaviour with high accuracy. It may be a competitive analysis technique in cases where significant additional analysis costs are outweighed by the savings made due to the results of higher accuracy.

The safety assessment of existing civil structures may be such a case. However, the output of NLFEM is a design load with no indication of a given exceedance probability and thus, implicitly, a safety level. When the target requirement of structural safety is a reliability index / accepted failure probability, the result of NLFEM therefore does not give a directly applicable answer as to whether the structure is sufficiently safe. Therefore, for the applicability of NLFEM, a safety format should be determined and accepted.

4.1.3 Innovative methods for the preservation and retrofitting of existing structures

The presentation by *Peter Tanner, Civil Eng. (IETcc-CSIC and CESMA Ingenieros)* focused on:

- Risk-based models and requirements
  The fundamental problem relating to the assessment of existing structures is to find an answer to the question as to whether they are safe enough for future use. Decision-making on structural safety using the approaches adopted in everyday practice is affected by a set of shortcomings, since risks associated with a specific infrastructure are not explicitly quantified. Therefore, the allocation of resources for risk reduction is often not optimal. Tools and rational risk-acceptance criteria are to be developed, intended for the practical application of explicit risk analysis methods. The use of such methods in structural assessment affords a series of significant advantages:
  - updated information may be taken into account for the verification of structural performance
  - system reliability may be verified
  - benefits from risk reduction or control measures may be quantified
  - rational decision criteria are available for the acceptance of sufficiently small risks
  - interventions may be optimised.
- Step-by-step examination improving accuracy of data
  The main difference between assessing performance in existing and design phase structures is that many characteristics whose values are merely anticipated in the latter can be measured in the former. A phased procedure is therefore normally used for structural assessment in which the accuracy of the models is enhanced from phase to phase by improving examination assumptions through updates of the initial general data. The most accurate way to apply actual site data would be to conduct a probabilistic analysis. However, such methods may not be suited to everyday use by practising engineers and are limited to the final phase of the staged assessment, if necessary. Structural safety verifications in the preceding phases are based on a similar partial factor formulation as adopted in structural design codes, in which the representative values for the variables and the partial factors can be modified on the basis of updated information.
  Tools are therefore being developed to accommodate site data by updating both the characteristic values of load and strength variables as well as the associated partial factors. Simple models are also needed to extend these tools, originally established for sound structures, to the reliability assessment of deteriorating structures.
- System reliability
  The partial factor formats available in current codes have been developed for structural safety verifications at cross-sections level. For this purpose, independent calculations are normally used for the establishment of internal forces and moments on the one hand, and the corresponding resistances on the other. According to such a procedure, the current partial factor methods do not take into account the effect of structural behaviour on reliability.

In structures with a ductile behaviour, redistributions of internal forces and moments are possible and the failure of one cross-section does not lead to the collapse of the system. In such cases, the probability of failure of the system is well below the probability of failure of the individual cross-sections. System rather than cross-section reliability should therefore be considered in the assessment of existing structures. Such an approach may lead to considerable benefits, particularly in the case of structures with a ductile behaviour.

- Risk control by means of monitoring
  Different causes may lead to the non-compliance of a particular requirement relating to an existing infrastructure. Many of the causes may be traced back to deviations from expected actions or resistances. The quantification of parameters relating to such influences may provide evidence about the degree of compliance of a given structure with a particular serviceability or safety requirement. Such parameters may therefore be called indicators and associated threshold values can be established on a risk basis, as well as admissible average frequencies for outcrossing.
  Indicators may be monitored and the measured values can continuously be compared to the threshold values previously established. Alarm systems may be installed which are activated in the event of outcrossing. Safety measures can therefore be adopted depending on the consequences of the observed non-compliance. Based on such an approach, and by using modern information technology, inspections of large infrastructures may be automated and optimised.

4.1.4 Present and future challenges of ageing concrete infrastructure in Norway

Prof. Rob Polder gave a presentation that was prepared by *Dr Claus K. Larsen (Norwegian Public Road Administration)*, who was unfortunately unable to attend. The presentation covered the following topics:

- Large maintenance backlog in Norway, (€ 0.5 - € 1 billion p.a.) which increases every year.
- The most relevant degradation mechanisms:
  — Reinforcement corrosion
  — Alkali-silica reaction (ASR)
- Developments needed in the field of assessment and inspection:
  — Evaluating the type and quality of data
  — Providing correct and reliable assessments
- Developing support for 'choice of action':
  — Develop criteria for choosing correct type of action
  — Determine the 'service life' of various actions
  — Develop new, reliable and cost-effective solutions
- Understand how design influences service life.

4.2 Defining the routes and formulating a common agenda

The final aim of the workshop was to formulate (1) a limited number of routes, and (2) specific points to tackle. This was achieved by means of a facilitated process in which, first, each of the four discussion groups (the speakers constituted a separate group), proposed three 'most promising routes' of development. These are summarised below (not prioritised):

- Life-cycle analysis and costing of maintenance methods.
- Methods for assessing remaining service life.
- Monitoring of different critical cross-sections.
- Baseline assessment – fast and cheap method for the majority of structures; high-accuracy methodology for critical structures.
- Quantifying the benefits of intervention.
- Cost estimate for residual life, using monitoring results.
- Unique guideline for structural reliability.
- Understanding the system behaviour of repair, the goal being to increase the service life of repair.
- System approach for assessment of existing structures, spatial variability until collapse.
- Codified framework for assessing existing structures.
- Effect of deterioration on structural performance – experiments and models.
- Broader application area of NLFEM models for structural reliability assessment.

Apart from the routes, the relevant input during the discussions included the following comments:

- 'One of the main challenges is to understand the current status of the structure on the condition curve.'
- 'For a large number of assets, a quick scan method such as image analysis is a promising technique to support decision-making.'
- 'The perception of service life should be on common grounds, in order to speak effectively about service-life extension.'
- 'From the point of view of the owner, technical problems and solutions should be translated into cost aspects.'

The three most promising routes were proposed and the necessary developments for each were fleshed-out in groups. The proposed routes and developments are described in the following sections.

4.2.1 Route 1: Life-Cycle Assessment and costing methodology

'Without Life-Cycle Costing method, nothing makes sense.' (for a decision-maker)
This topic had been named as a priority by a majority of participants. The need for quantitative, preferably monetisable, decision support was articulated in the group discussions. Infrastructure asset managers want to:

- Determine the remaining life of existing structures.
- Be able to determine the costs relating to various structural upgrading and renovation measures.
- Based on quantified information about the current condition supported by measurement data, gain knowledge about the time-dependent impact of repair and the remaining service life.
- Optimise maintenance planning.

To realise these goals, life-cycle assessment and costing methodology should be developed for practice. This can be translated into the following needs:

a. Development of an applicable framework for Life-Cycle Costing.
b. Determining the time-dependent behaviour of various maintenance measures and their cost aspects.
c. Development of decision-support tool.
d. Extend costing methodology to environmental effects.

4.2.2 Route 2: Framework for re-assessment of existing structures

Some comments from the discussions:

- 'We need a guideline that doesn't need new research. Something fast, that is better than what we have now.'
- 'In academic research we assume that information is available – but this is not the case in practice.'

In several discussions, as well as in the speakers' presentations, the need for a developed framework to re-assess existing structures was emphasised. Practitioners are calling for a framework (ultimately in the form of a code) to deal with both assessment/evaluation and interventions. A four-step framework was developed by the discussion group. The steps are shown in Figure 4.

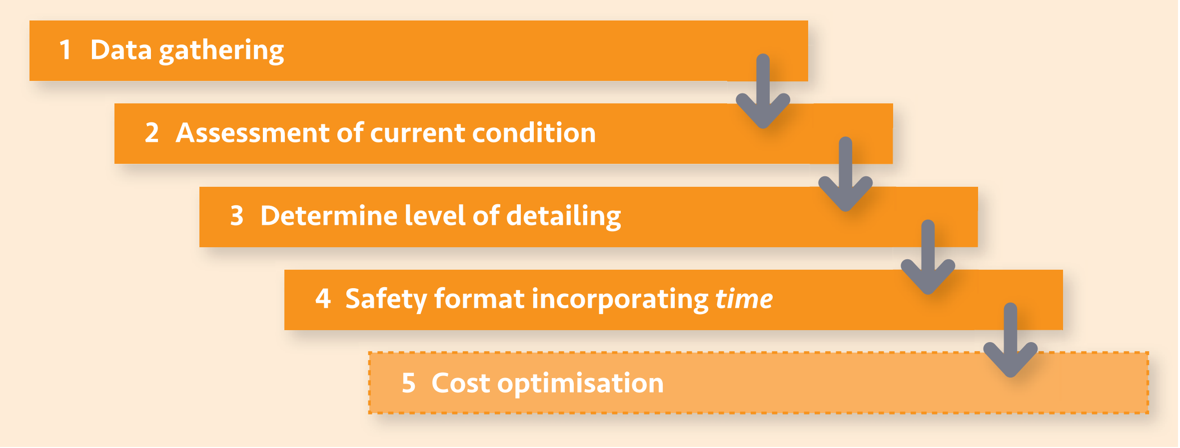

Figure 4. Framework for re-assessment of existing structures

First, a methodology for data gathering should be codified. In practice, a large number of civil structures (e.g. bridges) must be kept sufficiently safe and fulfil functional requirements. This requires 'fast and cheap' methods, enabling the assessment of several structures and possibly incorporating updating. The second step, based on the initial data, is the assessment of the current condition. In the third step, based on the results of a simple assessment of the current condition, the level of detailing should be determined. For structures in which safety is questionable, high accuracy methods are needed. On the one hand this refers to the value of information (What to measure? How precisely?) and on the other hand to the detail of the analysis method (up to complexity such as using non-linear finite element methods). The fourth, highly relevant step to adapt for practice is the incorporation of time-dependence in safety formats. Although implicitly taken into account in certain loading schemes (e.g. traffic load on bridges in the codes in the Netherlands), the development of structural safety in time is not determined in current practice.

These steps will lead to (more realistic) input for cost optimisation. This refers to the ultimate goal of infrastructure maintainers in the field of decision-making.
The following are specific aims for research relating to the above framework:

a. Determine guidelines on what to measure and monitor and how.
b. Determine methods for incorporating qualitative information in a quantitative way.
c. Determine how to use the information gathered to update load parameters, resistance parameters and partial factors in day-to-day engineering.
d. Develop practical models for resistance of existing structures.
e. Develop suitable reliability levels based on cost optimisation and human safety requirements.
f. Develop a framework for adjustable partial factors.

4.2.3 Route 3: System behaviour

The third main challenge was articulated in several presentations and was chosen as a priority by a majority of participants. There seems to be a common understanding that there is a knowledge gap in the field of the behaviour of structures as a system, and the impact of this behaviour on overall structural reliability. First, it is not known (in day-to-day engineering practice) how to evaluate existing structures based on their 'real' failure mechanisms: cross-sectional capacity is considered instead of system capacity. On the other hand, spatial variability (mainly of strength parameters) is not fully incorporated in structural re-assessment.

Current performance-based structural reliability criteria (i.e. accepted probabilities of failure) refer to one specific element or single cross-section, for example a beam in bending. In reality however, there may be some redundancies in the system, since structures differ in robustness. This aspect is not quantified and there is little knowledge available on how to realistically assess the overall failure probability (thus safety) of a civil structure.
The following necessary technologies should be developed in order to address the knowledge gap in system behaviour:

a. How to define and assess system reliability, for ductile or brittle behaviour.
   - What is the effect of local behaviour on global structural reliability?
   - Develop different acceptance criteria and safety format for the system and section levels.
   - Develop load models for the system and section levels.
   - Develop a common rationale for robustness assessment of existing structures.
b. Perform large-scale tests to calibrate the models.
c. Methods and requirements for non-destructive testing, in order to determine properties.
d. Better understanding of soil-structure interaction.

In order to model structures more realistically and take more advantage of 'hidden safeties', developments in the non-linear finite element analysis are required. These are:

e. Development of NLFEM models for existing structures for different failure mechanics.
f. Development of a safety format for NLFEM calculations.

Furthermore, material degradation models should be better incorporated in the analysis of existing structures. To achieve this, the following steps are important:

g. Develop probabilistic models for local and global deterioration.
h. Perform small- and large-scale experiments on deteriorating structural elements.
i. Couple deterioration to reliability assessment in a certain (remaining) lifetime.

5 Steel structures

The parallel session about ageing steel structures was led by Prof. Johan Maljaars from TNO & Eindhoven Technical University (the Netherlands). The ten participants from various fields (academia, engineering offices, governmental engineering offices) gave their input to the session, setting the framework for the innovation routes.

The presentations and discussions are summarised in the following sections.

5.1 Extending the service life of steel bridges in the Netherlands

Frank van Dooren MSc (Rijkwaterstaat, GPO department Bridges and Viaducts) presented two main critical aspects of ageing infrastructure in the Netherlands: local fatigue issues in steel bridges with orthotropic decks, and static strength issues in steel bridges.

For the topic of fatigue in steel bridges, a list of topics requiring further development and research was proposed:

- Safety-approach fatigue calculations (γ_{mf}, γ_{ff}): the partial factors for fatigue in existing structures given in standards need to be improved.
- Improve Eurocode 1993-1-9 + 1993-2: update classification of bridges and improved calculation demands.
- Improve EN 1991-2: updating the fatigue load model 4 and 5 for existing bridges, with the help of measured data.
- Improve the demands for extracting hot-spot or nominal stresses from Final Elements (FE) for fatigue calculations, at the design stage.
- Disseminate the knowledge of crack-propagation calculations with the prospect of determining safe inspection intervals.
- Develop new techniques to reduce the stresses in orthotropic decks.
- Improve detection/measurement and prediction techniques (individual bridges).
- Give attention to global fatigue in the main girder system.

Two promising developments were referred to in this presentation:

a. Bridge monitoring with real-time update for crack extension models.
b. Virtual monitoring concept (research project funded by the European Commission): bridge monitoring technologies are being developed to prove that many bridges are safe and that the service life can be extended to the benefit of more sustainable road-asset management.

The topic of static strength for steel bridges in the Netherlands is related to the level of conservatism of the Eurocode in predicting the static traffic loads for existing bridges. The developments required in relation to the uncertainty in the definition of load for existing bridges are listed below:

- Expanding the number of Weigh-In-Motion (WIM) locations (also on local roads) for a better definition of the loads on existing bridges.
- Expanding long-term load-effect measurements for a better (local) definition of the loads and load effects on existing bridges.
- Expand the existing bridge code to make use of the above effects.
- Develop 'enforcement methods', using monitoring systems.

5.2 Practical experience, solutions and research into steel bridges in Germany

Heinz Friedrich Dipl.-Ing. (Federal Highway Research Institute, BASt) gave a presentation about the practical experiences, solutions and research in Germany with respect to steel bridges. There is awareness of the problem of increased traffic on old bridges, but the support tools for deciding whether to replace or renovate are too complex to be used in day-to-day practice. A number of proposals were made for the Replacement option in the decision tree:

a. Design and construct bridges for the future (predicted) traffic.
b. Use fatigue-friendly details.
c. Work with two superstructures.

The relevant innovations for the Renovation option are listed below:

d. Use of a layer of High Strength Concrete (HSC) on the deck or develop another economically and technically efficient solution to lower the stresses in the deck.
e. Strengthening to be done from the top (less complicated) and should be beneficial for all fatigue-prone details.
f. In all cases, new renovation techniques should be either high-tech when carried out in workshops, or low-tech on-site.
g. Find new welding and repair techniques with ongoing traffic.
h. New welding techniques and materials are needed that are compatible with old steel in existing bridges.
i. Find the cause of and solution to the problem of new cracks occurring in existing bridges when a new asphalt layer is added (is it a problem of new cracks or existing hidden cracks?).

Regarding the static strength of existing steel bridges in Germany, the issue of major concern is the inability of the main structural system to take over extra weight from steel from fatigue-friendly repairs. A better distribution of stresses can be obtained with a thicker asphalt layer.

5.3 Defining routes and formulating a common agenda

The goal of the plenary session was to decide on the most promising routes for extending the service life of steel bridges and to define the important innovations to be dealt with.

The most promising routes are divided into two areas: fatigue and static strength of ageing steel bridges. Each of the areas has four aspects on which research and developments should focus. The routes are shown in Figure 5.

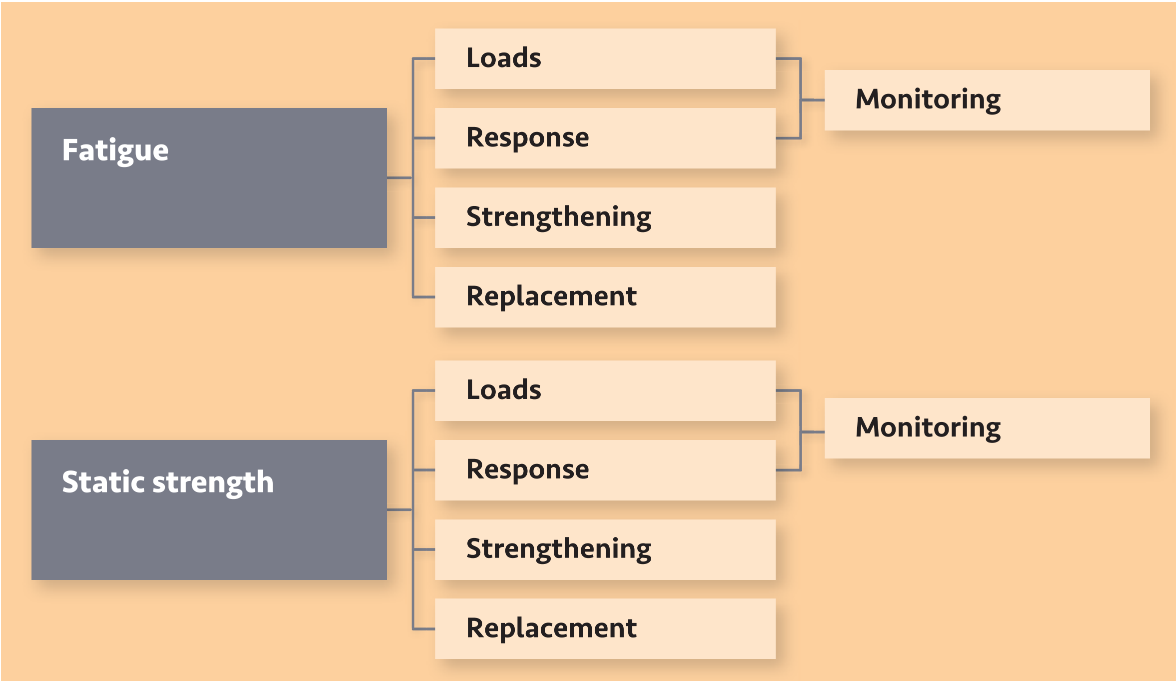

Figure 5. Scheme of the most promising routes for extending the service life of steel bridges

A critical aspect of the decision-making process is to know the condition of the assets as precisely as possible. Also, the different options that are available for strengthening these assets is an important aspect in the evaluation process. A decision-making tool for the assessment of existing bridges that incorporates the aforementioned criteria represents a crucial development for both routes presented in Figure 5.

The innovations needed for the routes are presented in the following sections.

5.3.1 Route 1: Innovations needed for the Fatigue route

1. Loads and response (monitoring)

Measuring and monitoring the stresses on representative bridges was recognised as an important tool which could provide relevant data to be used for all the bridges on a highway. The following are needed for this:

a. Accessible monitoring systems with extended life.
b. Standardisation of the data analysis and generalisation of the measured stresses.
c. Use the measured data to obtain better estimations of fatigue loads and to update the fatigue load model from Eurocode.
d. Harmonisation of the existing standards and improvement of the partial factors.

2. Strengthening

With regard to strengthening steel bridges against fatigue, innovations and research were proposed on two levels: a broad level and a more focused one.
For the broader innovations, better exploration into the following aspects was proposed:

e. Ways of strengthening movable bridges.
f. Development of less high-tech techniques for strengthening.
g. Looking into the ways of strengthening the main girder system for fatigue resistance.

For the more focused techniques and innovations needed, the main points of interest are:

h. Other solutions of strengthening the deck (e.g. using a composite deck plate).
i. Development of 'cold' (i.e. no-weld) repair techniques for short, medium and long-term structured life extension.
j. Repair techniques done with ongoing traffic.
k. Find and quantify the effect of post-weld treatment on enhancing the life of existing structures.

3. Replacement

With regard to the replacement of ageing structures, it was mentioned that there are plenty of lessons to be learned for new bridges, relating not only to the technical aspects but also to planning for monitoring and inspection.

l. Research should focus on bridge-renewal techniques carried out in extremely limited spaces.
m. The robustness of design should be better regulated in norms.

5.3.2 Route 2: Innovations needed for the Static strength route

1. Loads and response monitoring

The research topics proposed in this area cover several issues, including:

a. The limitation of loads and the enforcement with the help of monitoring systems or by setting clear regulations regarding heavy axles allowed on the roads.
b. Improved load models for the Ultimate Limit State (ULS) represents another point of focus for this route: this could be done by using the measured data from WIM systems to predict ULS loads and by implementing a uniform methodology of extrapolating the static loads in codes/norms/manuals.

2. Strengthening

With regard to strengthening the static capacity of steel bridges, it is necessary to look into improved methodologies and better techniques, and develop manuals. The focus should be on all assets, including smaller bridges.

3. Replacement

The robust design of bridges for future traffic loads should be regulated in norms (as for Route 1 – Fatigue).

6 Call for action

Maintaining a reliable and safe (transport)infrastructure network is the concern of every asset owner. During the workshop we saw that the budgets required to maintain the current infrastructure network will increase fast. The examples from Germany, Norway and the Netherlands are all proof of annual re-investment needs and maintenance backlogs of many billions of euros.

The effectiveness of replacement programmes is of concern to all citizens, as is the safety of civil structures. We call upon **national and European policy-makers** to exert their influence on programmes such as Horizon 2020 and Infravation, to encourage and support the building and sharing of knowledge on extending the service life of civil structures. During the workshop, the main focus points for engineering were identified. It is now time to take action. To reach an optimum in both the short and the long term, knowledge of existing structures has to be developed, existing academic knowledge should be continuously made available to practitioners in codified format and, at the same time, existing and new knowledge on structures should be translated into (life-cycle) cost aspects.

The challenge of dealing with ageing infrastructure cannot be addressed in an effective, efficient and sustainable way at the local and national levels alone. We also call upon **European knowledge institutions** to accelerate the building and sharing of a common knowledge base in the field of existing structures. Existing working groups or platforms such as fib (International Federation of Structural Concrete) and RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) provide a framework for working on several of the most urgent topics.

The workshop was a unique event, during which experts from all over Europe jointly formulated the following most promising routes:

- For concrete structures, the following developments are needed:
  - Quantitative, preferably monetised decision support for the management and maintenance of existing infrastructure.
  - Practical codified assessment guidelines for existing structures.
  - Advanced models of structures:
    - Modelling real failure mechanisms, avoiding hidden safeties in structural models.
    - Developing alternative structural models for deteriorating structures.
- For steel structures, the following innovations are needed for the Fatigue and Static Strength routes:
  - Loads and response (monitoring).
  - Strengthening.
  - Replacement.

Let us continue to work together, by disseminating this agenda and using it in our own organisations. Together we can change the future by carrying out this joint research agenda to prevent a future with spiralling maintenance costs and considerable nuisance for road users!

Appendices

Appendix A: Plenary presentations

A-1 Arie Bleijenberg MSc (TNO)- Extending service life of civil structures: Welcome!

A-2 Prof. Werner Rothengatter – KIT and advisor to the Pällmann Commission and Daehre Commission (Future of transport infrastructure financing) - Challenges of Ageing EuropeanTransport Infrastructure

A-3 David Ashurst CEng MICE – (Associate Director, ARUP) - Existing UK Bridges Infrastructure

Appendix B: Parallel session presentations: concrete structures

B-1 Prof. Robby Caspeele (University of Ghent): Safety of existing structures: linking theory and practice

B-2 Prof. Max Hendriks (Norwegian University of Science and Technology): Future in FEM for concrete structures

B-3 Peter Tanner, Civil Eng. (IETcc-CSIC and CESMA Ingenieros): Innovative methods for the preservation and retrofitting of existing structures

B-4 Dr Claus K. Larsen (Norwegian Public Road Administration): Present and future challenges of aging concrete infrastructure in Norway

Appendix C: Parallel session presentations: steel structures

C-1 Frank van Dooren MSc (Rijkswaterstaat): Experience and future challenges with existing steel civil structures in the Netherlands

C-2 Heinz Friedrich Dipl.-Ing. (BASt): Practical experience, solutions and research into steel bridges in Germany