DECISION SUPPORT THROUGH MULTIPLE MODELS AND PROBABILISTIC SEARCH

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ABSTRACT: Finding good models of behaviour is important for explaining the performance of structures in service. Engineers often use complex models that require important assumptions which are adopted without adequate justification. Our approach is to define sets of candidate models through filtering large numbers of possible models with observations and trends in measurement data. An optimisation approach has been employed for identifying good models through the use of the algorithm, PGSL. A case study of a bridge in Switzerland is described to illustrate our approach and candidate models that reasonably explain its behaviour have been identified.

KEYWORDS: model-based reasoning, measurements, monitoring, diagnosis

1. INTRODUCTION

Finding good models for explaining a given set of observations is a difficult engineering task. For example, repair plans for structures with serviceability deficiencies often require accurate knowledge of the real behaviour of the structure. A lack of such knowledge may influence the cost and the efficiency of the repair plan.

A good model is also important for finding answers to questions that arise during the life of a structure. For example, the following questions may be relevant:

- Is something wrong with the structure? (damage detection)
- What might be the most critical problem in a particular situation? (damage prediction)
- What is the state of the structure (cracks, creep, support displacement, etc.)? (serviceability problem)
- What might be the state of the structure after several years? (prediction)
- Is the structure capable of performing well in a new situation? (adaptation)
- Which solutions are more appropriate for a particular deficiency? (repair)
- Is it better to repair now or to delay it? (management)
- What kind of new observations or measurements are necessary for making good decisions? (monitoring)
- Is the repair plan successful? (monitoring)
- Do we have less problems with certain type of structures, repairs, etc.? (design)
- What is the risk of failure of a structure? (structural safety)
- etc.

Models provide information that is employed for design as well as during other activities through out its life cycle, such as monitoring, diagnosis, intervention and prediction. Tasks of modern engineers are not only found in design and construction, as it has been in the past, but are now increasingly present throughout the entire structural life cycle. As a result, structures are increasingly equipped with measurement systems so that engineers may acquire a better understanding of real behaviour during service lives.

This paper focuses on the use of measurement data for identifying feasible models for explaining behaviour of structures. The example of the Lutrive Bridge in Switzerland illustrates our approach.

2. CURRENT METHODS

For evaluating a structure during its service life, the following sources of information are available:

- **models** (numerical, analytical, etc.) and,
- **observations** (visual information, measurements data, etc.).

2.1 Models

Models are widely used for simulation, design, diagnosis and prediction [Chantler *et al*, 1998, Salvaneschi *et al*, 1997]. However, current approaches have several weaknesses. For example,

- Modelling assumptions are made without adequate justifications and verifications.
- Simple models are often not compared with more complex ones in order to determine whether or not more complex models are more appropriate.

It has been demonstrated that a large number of possible models exist for full-scale civil engineering structures such as bridges [Raphael and Smith, 1998]. Engineers often can not systematically consider the vast choice of possible models and consequently, they employ only a small subset of them. It is rarely possible to evaluate multiple modelling possibilities systematically by conventional means. In this paper, it is proposed that computer assistance for selecting appropriate models provides support for monitoring and maintaining civil engineering structures.

2.2 Observations

Observations can be qualitative (visual information) as well as quantitative (measurement). The former is already being used in practice, while the latter is not available for all structures. Most bridge management systems (for example, PONTIS, KUBA, BRIDGIT, etc.) do not focus on measurement data. However, several trends are emerging that will increase the availability of measurement data. For example, the use of fibre optic sensors [Inaudi, 1997], inclinometers [Burdet and Zanella, 2000] and GPS technology [Dodson *et al*, 1999] demonstrate advantages of bridge monitoring. Furthermore, sensors are becoming more reliable and cheaper while data storage and management equipment are more portable, less expensive and faster.

Most work on theoretical modelling does not make use of measurement data. Techniques that do make use of measurement data, for example [Kabe, 1985, Sohn and Law, 1997], often aim only to correct parameters such as stiffness coefficients. Characteristics of behavioural models that explain the change in stiffness coefficients are not explicitly available using these techniques.

In the numerical modelling community, there is a tendency to aim at very high levels of sophistication of models. At the same time, there is usually a significant level of uncertainty in measurement data. Uncertainties in measurement data as well as the effect of uncertainty of model parameters on model accuracy are not often considered simultaneously. An outline of software which supports engineers for such tasks, is presented in the next section.

3. COMBINING MODELS AND OBSERVATIONS FOR DECISION SUPPORT

Models are often numerous and observations usually contain much information. It is important to combine them to arrive at feasible models for better decision making related to monitoring, diagnosis, repair and prediction. Our aim is to improve interaction between engineers, models, measurement systems and data, as shown on Figure 1. Important modules and their relationships are explained below:

3.1 Modules

Model library: The model library contains a set of models with explicit assumptions and methods for computation of behaviour.

Model retrieval/ calibration: This module compares measurement data with model results. Models are initially selected by examining trends in measurement data. Each of the selected models is then analysed to find out how the predicted behaviour matches with measurements. Global search techniques such as PGSL [Raphael and Smith, 2000] are used to calibrate parameters when only ranges of values of parameters are known.

Qualitative evaluation: This module assists engineers when comparing data with calibrated models to identify suitable candidate models.

3.2 Relationships

Engineer-model interaction (Link A, Figure 1): Users either define models manually or models are generated automatically through the technique of model composition [Raphael and Smith, 1998] by selecting a set of assumptions. For each model that is generated, parameters related to behaviour such as deformations, curvatures, slopes, etc. are automatically calculated. The term model does not refer to a point solution, but a set of solutions defined by a range of values for its parameters.

Model library-measurement system interaction (Links D, E, C, Figure 1): Results of models may be used to help define the most appropriate measurement that is required. An important consideration is that the measurement should provide enough information to identify candidate models from among the set of all possible models. This is possible only if the measurement data is able to discriminate between features of behaviour of different models. The information about the sensitivity of instruments along with the model precision is also used to choose the best measurement system.

Engineer-data interaction (Link F, Figure 1)**:** Users provide visual information about the structure such as cracks, deformations, general aspects, etc.

Engineer-model retrieval module interaction (Link B, Figure 1)**:** Users define rules for retrieval and for comparing measurement data with model results. A common method of comparison is by computing the root mean square difference. Many other techniques may also be appropriate. Users are also able to select subsets of measurement data for sensitivity analyses.

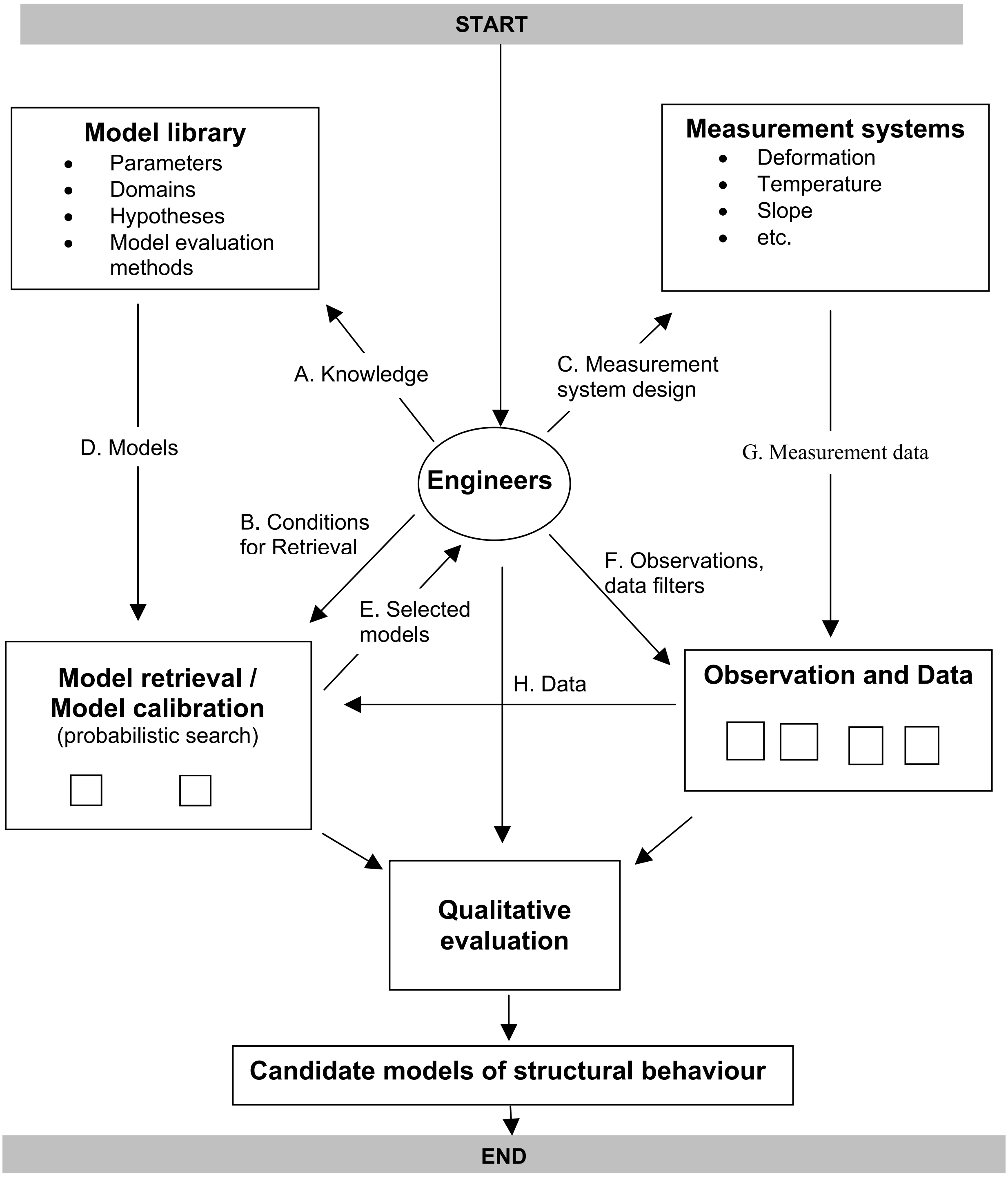

Figure 1. Entities and relationships in the decision support system. Flow of information between modules is shown with arrows. Engineers compare models with data and observations in order to identify the most appropriate models.

4. LUTRIVE BRIDGE EXAMPLE

4.1 Description of the Bridge

The Lutrive highway Bridge was constructed in 1972 using the cantilever method with central hinges. Two bridges were built (one for each direction of traffic) with a length of 395 m. each and a maximum span of approximately 130 m. The longitudinal section is shown in Figure 2:

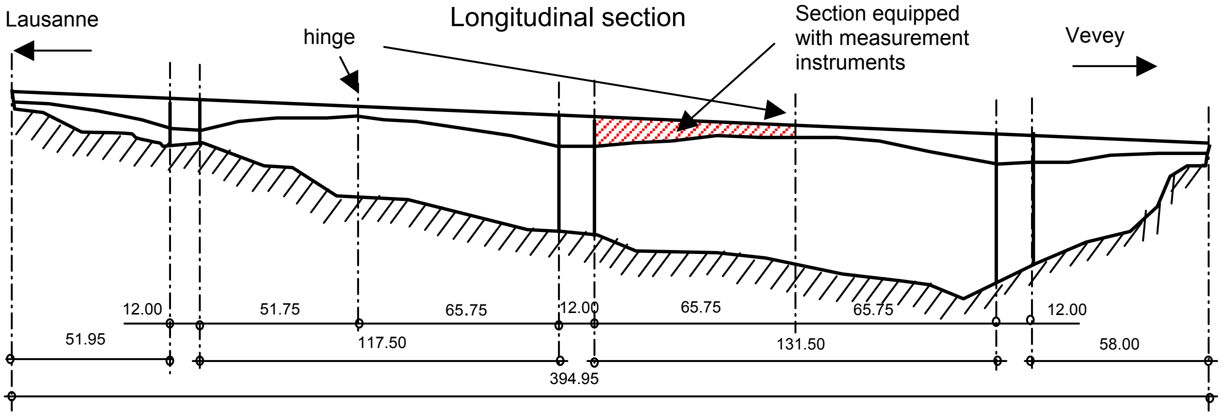

Figure 2. Longitudinal section of Lutrive Bridge (values in meters)

The cross-section of the bridge is a pre-stressed box-girder with variable inertia. The maximum height is 8.50 m. at the column and 2.50 m. in the mid-span, at the hinges. More information about the bridge can be found in [Burdet and Badoux, 1999]. A brief history of the bridge is given below:

• 1971-1972:	Construction of the bridge
• 1973, 77, 78, 80, 85, 86:	Annual optical level meter measurements
• 1986:	An engineering office was given the contract to survey the bridge after large deformations were observed at mid-span
• December 1988:	External pre-stress added to the two bridges
• 1988-1999:	Displacement on the south bridge increases. New measurement systems are installed on the bridge, including a hydrostatic levelling system (1988)*, and fibre optical sensors (1996)**
• November 1997:	Load tests with fibre optic sensors **, inclinometers*, and optical level meter *
• December 1999:	New additional external pre-stress added to the south bridge

*[Burdet and Fleury, 1997]
**[Perregeaux, 1998, Perregeaux *et al*, 1998]

4.2 Models of Lutrive Bridge:

Finding a good model for Lutive Bridge and the right explanations for abnormal increases in displacements have remained a challenge for several years. Various hypotheses involving parameters such as creep, pre-stress and joint characteristics at mid-span have been made. New external pre-stress has been added twice on this structure in less than 30 years in order to correct serviceability deficiencies.

For this example, model changes over time have not been analysed. Only the task of defining a good model for a particular point in time is studied. The situation that is analysed is a load test that was conducted in 1997. The advantage of this case is that knowledge of the loading including positions on the structure is available.
One section of the bridge was equipped with instruments placed symmetrically on both sides of the box-girder. Measurements systems, part of measurement data and a sample of models are presented below:

4.2.1 Measurement systems

- Fibre optic sensors at the following five longitudinal positions [Perregeaux 1998] from the column in the Lausanne direction:
  8.4m., 20.4 m., 32.5 m., 44.5 m., 56.8 m.
- Inclinometers at four positions from the same column [Burdet and Fleury, 1997]:
  16.1 m., 29.5 m., 49.3 m., 65.75 m.
- Optical level meters at four positions from the same column
  [Burdet and Fleury, 1997]:
  11.9 m., 29.9 m., 47.8 m., 65.75 m.

4.2.2 Measurement data

Each measurement system provide the following measurement data:

- Two fibre optical sensors placed on the upper part and lower part of an element define the curvature by the relations derived from simple beam theory:

$$\frac{1}{r_m} = \frac{l_{inf,2} - l_{sup,2}}{Y \cdot l_1}$$

r_m : *mean radius of curvature*
l_1 : *initial length of upper and lower sensors*
$l_{sup,2}$: *final length of upper sensor*
$l_{inf,2}$: *final length of lower sensor*
Y: : *distance between upper and lower sensors*

- Inclinometers give the slope of the cross-section. [Burdet and Fleury, 1997]
- Optical level meters give the vertical displacement of cross-sections. [Burdet and Fleury, 1997]

4.2.3 A sample set of models

A sample set of models has been defined for the Lutrive Bridge (Link A, Figure 1). The following points are relevant to the section of the bridge which is examined:

- Only the section that is limited from the column to the mid-span has been analysed with models 1, 2, 3, 4, 5 and 6.
- The complete structure has been analysed using models 7 and 8.

Characteristics of each model are presented in Figures 3a-3h.

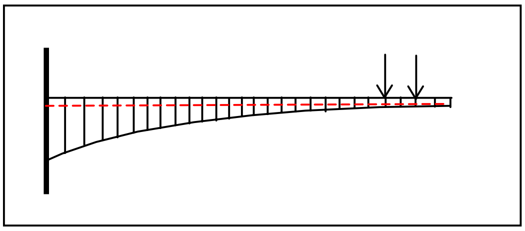

Figure 3a. Model M1

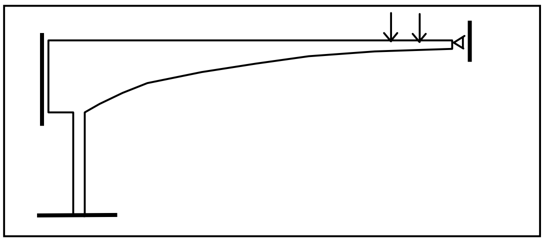

Figure 3b. Model M2

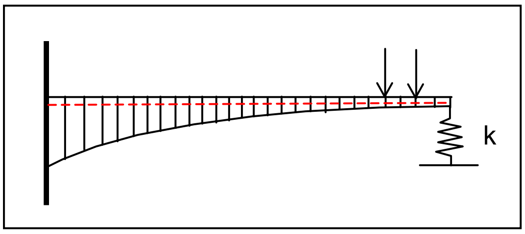

Figure 3c. Model M3

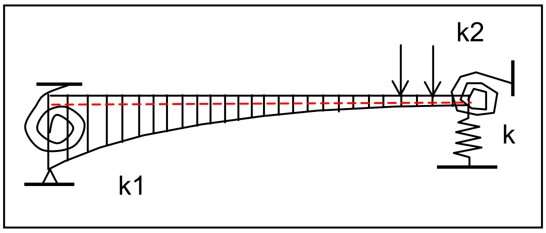

Figure 3d. Model M4

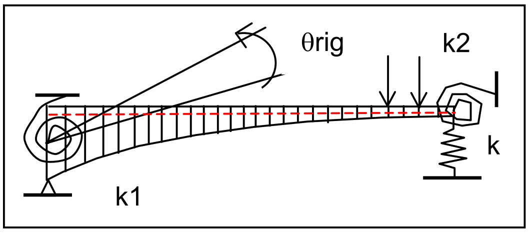

Figure 3e. Model M5

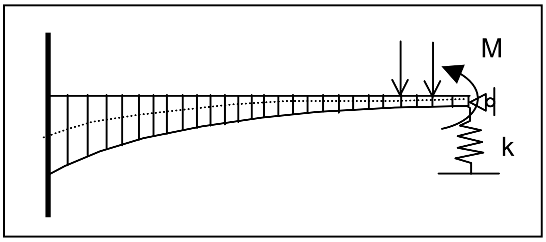

Figure 3f. Model M6

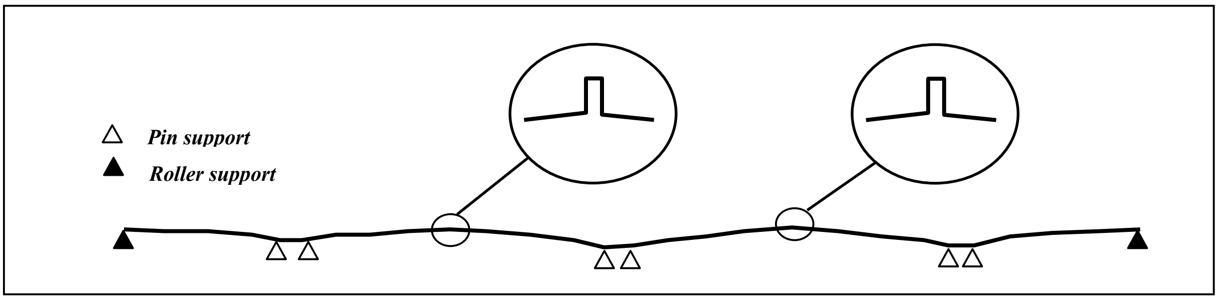

Figure 3g. Model M7

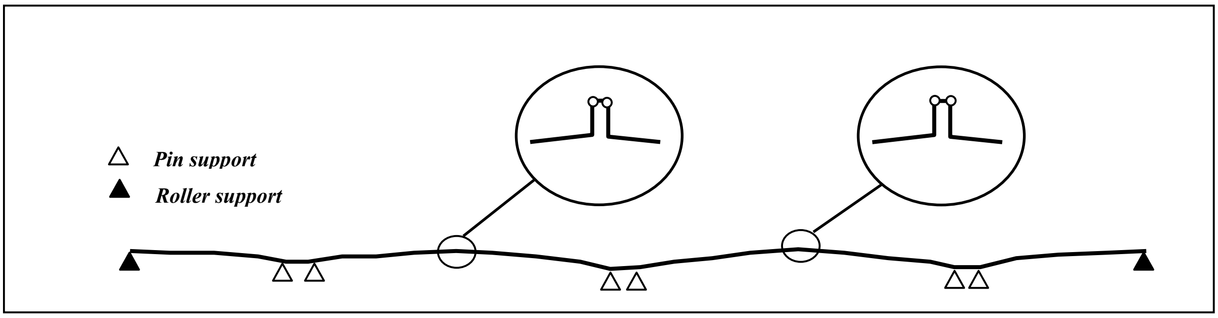

Figure 3h. Model M8

M1: Design model *[Perregeaux 1998]* **Description:** • Cantilever bridge with parabolic section profile (variable moment of inertia) • Evaluated analytically **Parameters:** • E: 38e6 [kN/m^2]	***M2: Design model*** *[Perregeaux 1998]* **Description:** • Cantilever bridge with parabolic section profile (variable moment of inertia) • Evaluated through finite elements modelling (MAPS) **Parameters:** • E: 32e6 [kN/m^2]
M3: Propped cantilever model **Description:** • Propped cantilever bridge supported on a spring at the propped end • Parabolic section profile • Evaluated analytically (force method, virtual work) **Parameters:** • E: 38e6 [kN/m^2] • I: from 5.129 to 138.89 m^4 • k: 17’114 [kN/m]	***M4: Beam with rotational and vertical springs*** **Description:** • Simply supported beam with rotational springs at both ends • Supported on a spring at one end • Parabolic section profile • Evaluated analytically (force method, virtual work) • Use of GPSL algorithm for calibrating value of parameters **Defined Parameters:** • I: from 5.129 to 138.89 m^4 **Undefined Parameters:** • E, k, k1, k2
M5: Beam with rigid body rotation **Description:** • Simply supported beam with rotational springs at both ends • Supported on a spring at one end • Parabolic section profile • Evaluated analytically (force method, virtual work) • Rigid body rotation at supported point • Use of GPSL algorithm for calibrating parameters values **Undefined Parameters:** • E, k, k1, k2, θrig **Defined Parameters:** • I: from 5.129 to 138.89 m^4	***M6: Finite element modelling with arch effect*** **Description:** • Propped cantilever bridge supported on a spring at the propped end • Arch effect with compression force • Parabolic section profile • Finite element model (MAPS) with beams • Bending moment at the end **Parameters:** • I: from 5.129 to 138.89 m^4 • E: 30e6 [kN/m^2] • M: 1000 [kNm] • k: 16’300 [kN/m]
M7: Complete finite element modelling of the entire structure **Description:** • Parabolic section profile • Finite element model (MAPS) with beams • Change of neutral axis position at mid-span • Features of sections provided by the civil engineer office that was commissioned to study the bridge (Realini & Bader) **Parameters:** • E: 30e-6 [kN/m^2] • I: from 5.501 to 151.543 m^4	***M8: Complete finite element modelling of the entire structure*** **Description:** • Parabolic section profile • Finite element model (MAPS) with beams • Change of neutral axis position at mid-span • Features of sections provided by the civil engineer office that was commissioned to study the bridge (Realini & Bader) • Hinges at mid-span **Parameters:** • E: 30e-6 [kN/m^2] • I: from 5.501 to 151.543 m^4

4.3 An algorithm for finding best solutions in solution spaces

For models that include parameters which may have a range of values, we employ an algorithm called PGSL [Raphael, Smith, 2000] for finding the best combination of values of parameters. The algorithm consists of minimising the root mean square difference which is calculated as the difference between the computed and measured values of parameters. For the Lutrive Bridge, this difference was minimised in separate runs for displacement, slope and curvature.

PGSL is a stochastic search algorithm based on the assumption that better points are more likely to be found in the neighbourhood of good ones. Points are generated randomly in the search space according to a probability density function (PDF) and they are evaluated using a user defined objective function. The user specifies the initial range of values of parameters. The algorithm dynamically updates the PDF such that more intensive search is carried out in regions containing good solutions.

Results with PGSL algorithm for finding good solutions for model 4 and 5 are shown below, Table 1.

Model No	Parameters used in optimisation	Results with PGSL algorithm				
		E [kN/m^2]	k [kN/m]	k1 [kNm/rad]	k2 [kNm/rad]	θ_{rig} [mrad]
4	displacement	50.00e6	28’076	9.99e19	2.8e-8	-
4	slope	28.34e6	15’625	9.96e19	2.64e-4	-
4	curvature	48.64e6	16’300	9.81e19	5.48 e5	-
5	curvature	48.64e6	16’300	9.81e19	5.48 e5	0.072

Table 1: Model calibration with PGSL algorithm (Model calibration Module, Figure 1)

4.3.1 Results

Results for displacement, slope and curvature for the different models and for data measurement are shown in Figures 4, 5 and 6. Only displacement and curvature has been calculated for numerical models.

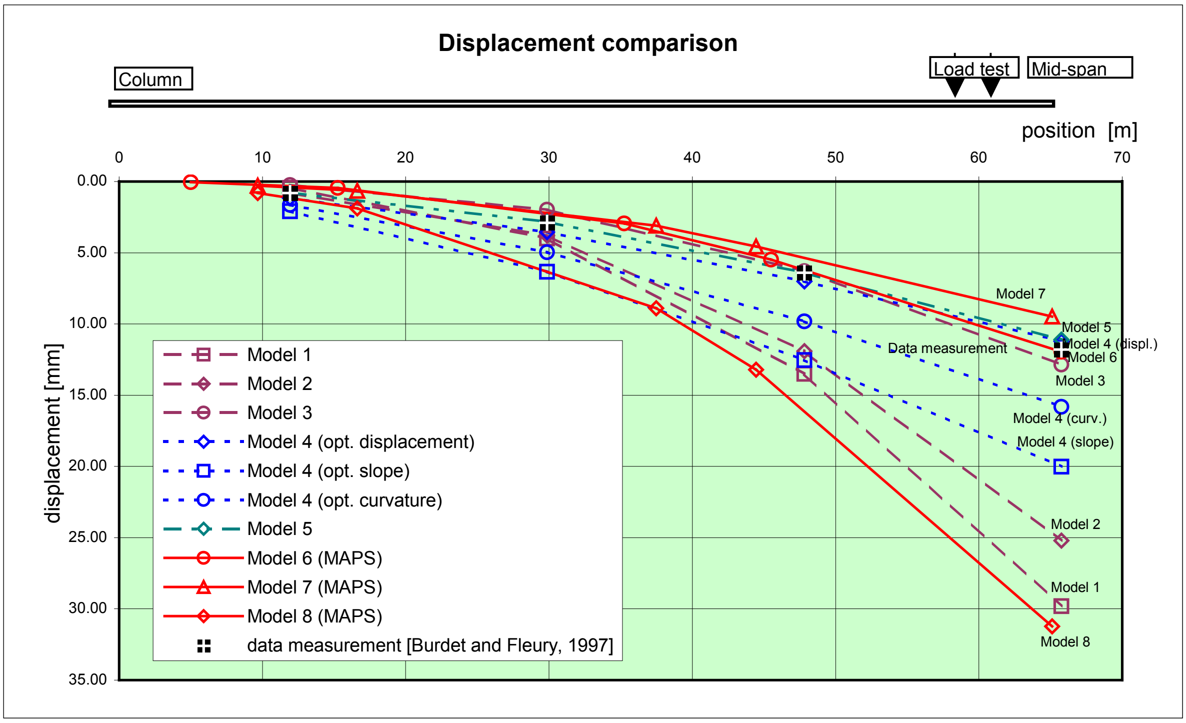

Figure 4. Displacement comparison

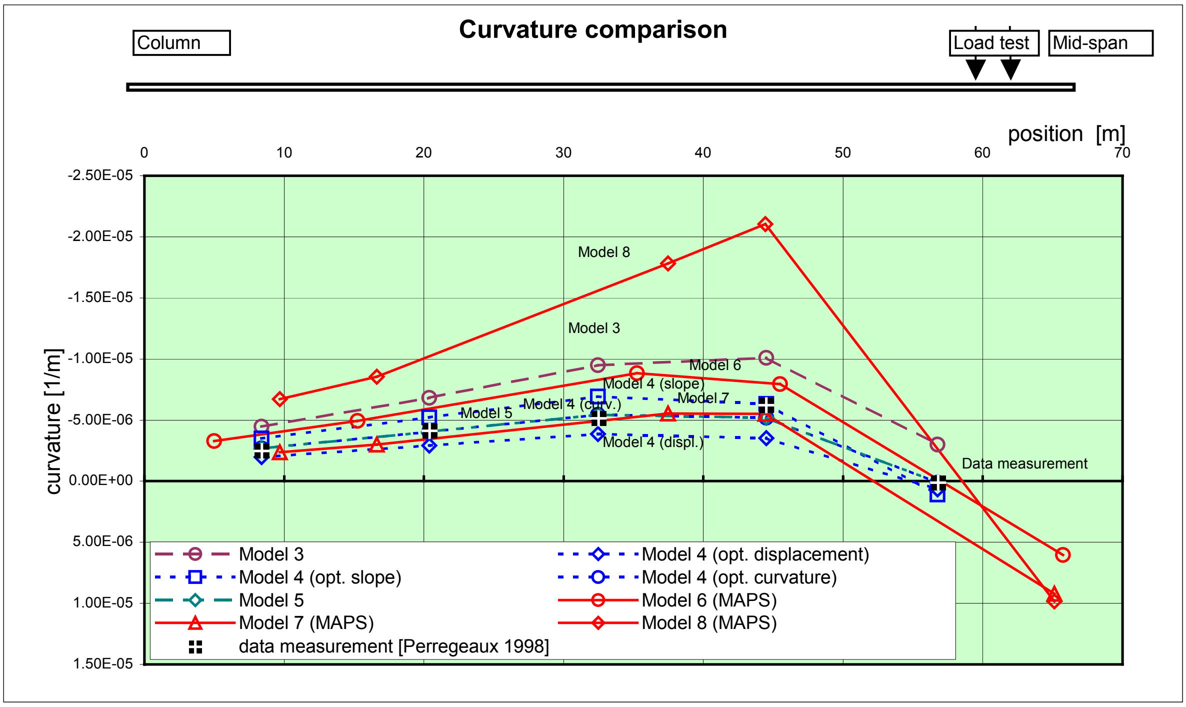

Figure 5. Curvature comparison

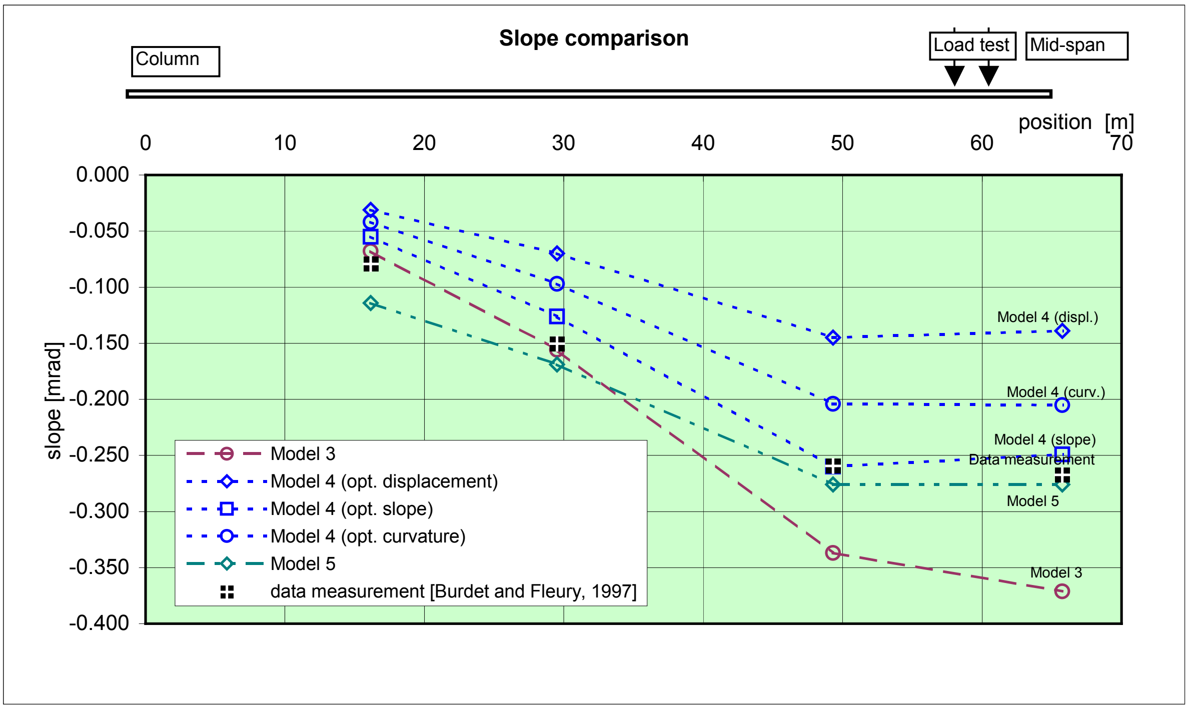

Figure 6. Slope comparison

4.4 Analysis of results

The three figures are used to classify models based on the percentage deviation (PD) which is computed by dividing the root mean square difference by the mean value of data points. Models are classified as good (PD <25%), reasonable (PD 25-50 %) and bad (PD > 50 %) as shown in Table 2.

Model No optimisation criteria is given in brackets	Criteria		
	Displacement	Slope	Curvature
1	Bad	-	-
2	Bad	-	-
3	Good	Reasonable	Bad
4 (displacement)	Good	Bad	Reasonable
4 (slope)	Bad	Good	Reasonable
4 (curvature)	Bad	Reasonable	Good
5 (curvature)	Good	Good	Good
6	Good	-	Bad
7	Good	-	Reasonable
8	Bad	-	Bad

Table 2: Evaluation of models (Qualitative evaluation Module, Figure 1)

The following observations and conclusions are made from this study:

- Selecting models through referring to only one type of observation is not sufficient. Displacement observations are not sensitive enough for evaluating candidate models. For example, model 3 has good match with measured displacement but not with slope and curvature measurements.
- Although finite element modelling is useful, it must be defined carefully. For example, a small change in boundary conditions greatly affects the results. In our case, changing a rigid link by a hinge between two bars has increased the displacement at mid-span by nearly a factor of three. Model 8 is completely wrong, and Model 7 has good match, but it is far too stiff (displacement and curvature).
- Having an exact match is nearly impossible. Increasing the number of parameters does not help.
- The process of identifying models that match measurements leads to examining models that have large numbers of parameters. The number of observation points must be greater than the number of parameters. A better match with more parameters does not necessarily mean that the quality of the model is better.
- The PGSL algorithm requires that the user enters the range of feasible values for parameters. In some models, optimal values of parameters were found to be on the limits of the range.
- Model calibration may be an interesting exercise for validating and deleting models. For example, Model 4 has not given good results for all three types of calibration attempts.

Two types of information have been generated by the study:

Qualitative information

- Models 5 and 7 have reasonable values for root mean square difference and the trends in measurement data correspond closely to the model behaviour. As a result, they belong to the set of candidate models.
- Curvature data measurements show a change in sign near the joint indicating that the mid-span joint transfers shear stress. This is not possible with models 1 and 2.
- Model 5 shows a favourable rigid body rotation at the support. Its influence is to increase the stiffness of the bridge. This could be explained by the arch effect creating a compressive force at the support. This is considered in Model 7.

Quantitative information

- Quantitative information related to values of parameters is more difficult to verify: For instance, Young Modulus of Model 7 is 30e6 [kN/m^2] whereas it is 48.6e6 [kN/m^2] for Model 5.
- Limiting the values of parameters to reasonable levels is necessary for practical use of PGSL. Otherwise, the optimisation algorithm converges to values that are impossible in practice.

5. WORK IN PROGRESS

There are several drawbacks to the method of finding the best combination of values using probabilistic search. For example, the algorithm retrieves isolated points in the domain of a model that gives minimum error, but does not consider the quality of the model as a whole. This difficulty is illustrated in Figure 7. The following definitions are used:

Measurement data domain: The set of data points representing the variations due to uncertainties in the measurement system and the operating environment (temperature, humidity, traffic, etc)

Domain of a model: space defined by the range of values of parameters in a model

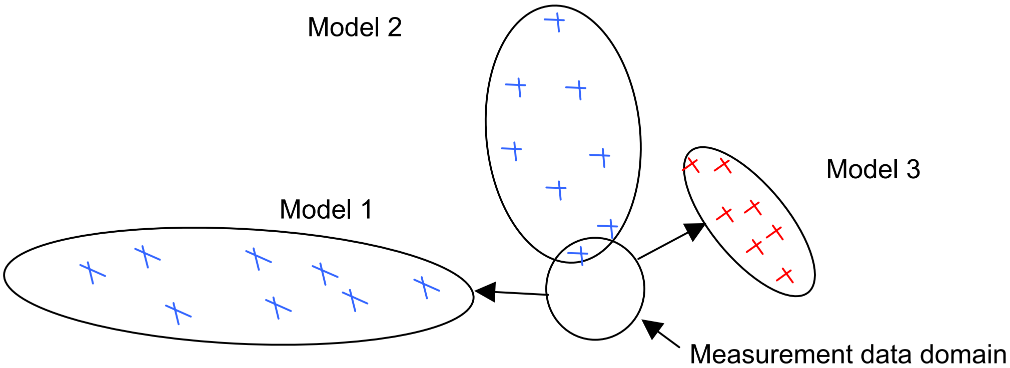

Figure 7. Domain defined by models (each cross express a set of value for parameters)

Two situations are of interest:

Situation 1: The measurement data domain intersects the domain of a model (for example, Model 2 in Figure 7). Here, it is interesting to find out the characteristics of the intersecting sub-domain.

Situation 2: The domain of a model does not intersect the measurement data domain. Instead of identifying individual points having least error, it is interesting to consider the overall behaviour of the model. For example, the domain of Model 1 in Figure 7 contains some points close to the measurement data. However, this might be the case because the model covers a large space of possibilities due to a large number of parameters that can be tuned. On the contrary, Model 3 gives an overall close match to the measurement data and its behaviour is less sensitive to change in values of parameters.

Probability density functions denoting the quality of solution points may be used for identifying interesting model sub-domains.

6. CONCLUDING REMARKS

It is often impossible to consider multiple models systematically without computer support. Searching for the right model through use of an optimally directed search algorithm has several advantages. Users need to define only the domain of models in terms of ranges of parameter values. The optimisation algorithm examines different possibilities and chooses the best one according to user-defined criteria. PGSL has been shown to be a useful tool for this task. Work is in progress to adapt the algorithm to define interesting sub-domains within a model-space instead of individual solutions. Through combining measurement data with models it is hoped that better decision support for diagnosis and maintenance of bridges will be made possible.

ACKNOWLEDGMENTS

This research is funded by the Swiss National Science Fondation (NSF) and the commission for technology and innovation (CTI). We would like to thank IBAP (Concrete Structures) at EPFL for data related to the load test on the Lutrive Bridge, and in particular Dr. O. Burdet and J-L. Zanella for their valuable contributions. We are also grateful to the civil engineering office "Realini + Bader et Associés" represented by Mr Beylouné for their interest and for information related to the bridge.

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