Automation in Construction 19 (2010) 1–10

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Review

Automation robustness of scaffolding systems strengthened with organic prestressing

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ARTICLE INFO

Article history:
Accepted 7 September 2009

Keywords:
Organic prestressing
Static control
Automation

ABSTRACT

The present paper describes a methodology to achieve operational and integrity validation of the structure-automation system on scaffolding systems with organic prestressing. Said methodology was developed for the first full-scale application of this new type of structure and it comprises software safety tools, experimental validation tests and checklist implementation. The main characteristics of the movable scaffolding system are highlighted and a description of the automation project and inherent control system is given, comprising operational modes, hardware and software issues. Finally, after providing recorded data for the structure-automation system in service, the feasibility and efficiency of the presented automation solution are confirmed.

Contents

1. Introduction

In the last decade several research and development works on organic prestressing have been carried out, including fundamental research [1], numerical analysis [2], experimental tests [3] and more recently the first full-scale application of a movable scaffolding system used in a bridge construction (in the north of Portugal) [4]. Results prove that this control system fosters the design of lighter structures

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0926-5805/$ – see front matter
doi:10.1016/j.autcon.2009.09.001

(due to significant internal forces' reduction), while simultaneously enabling enormous service deflection reductions [3,4]. The greater part of the aforementioned research process lies in the application of organic prestressing on scaffolding systems, which is an organic prestressing preferential application field, due to the high "live load/dead load" ratio.

Since the initiation of Organic Prestressing System (OPS) implementation [5], the development of a strategy to ensure the robustness of the structure-automation system was identified as a critical issue. Although, in general terms, the automation robustness requirements of the presented solution are similar to those required for other automation applications [6], the specific aspects, namely the structural importance of the automation system, clearly call for a systematically deeper approach to all operational and integrity failure or error sources. That is the main goal of this paper.

The first full-scale application structure is an underslung movable scaffolding system comprising 4 main truss box girders [4]. Each girder is strengthened with an organic (auto-adjustable) prestressing system, in which the prestressing jacks (actuators) have the capacity to impose stress variations on prestressing cables in accordance with a control algorithm.

The function of the OPS automation project is to provide an automatically adaptative variation of prestressing force (introduced via the prestressing cables) in order to minimize mid-span deflection due to external loads (principally during the concrete pouring and deck prestressing stages).

The main objective of the operational and integrity validation methodology is to ensure that OPS does not implement mid-span deflection control actions if unexpected situations (errors, failures or even structurally inadequate responses) occur. In structures with organic prestressing, automation is to be considered a structural issue thus, its robustness is essential.

Said methodology is presented after a brief sequence of descriptions of the movable scaffolding system, the OPS control algorithm and the OPS automation (both developed for the first full-scale application).

2. Movable scaffolding system strengthened with OPS

The full-scale structure where OPS was first applied is an underslung movable scaffolding system which comprises 4 main girders [4]. The girders are modular trusses with a transversal section of 1.25 m × 2.00 m. During the concrete pouring stage, each girder is supported on the bridge piers with a span length of 30 m. The principal loading extension (concrete pouring) is also 30 m but "starts" at $L/5 = 6$ m ahead of the back support and "ends" at the extremity of a 6 m long cantilever (not reinforced with OPS). In the launching stage, conventional movable scaffolding components are used (bogies, launching noses, etc.) and OPS is not relevant. Each girder is reinforced with 2 sets of actively controlled prestressing cables deviated by 2 deviation shores at L/3 of the span (see Fig. 1).

The OPS main elements–introduced on each girder–are 1) the actuator in the *organic anchorage*, 2) the unbonded cables, 3) the sensors and 4) the electronic controller in the girder control unit (Fig. 1).

3. Control algorithm

The OPS automation comprises 2 main operational modes which are selected according to the corresponding stage of the construction cycle. The *concrete pouring mode* algorithm (the most important mode) is a feedback control algorithm which performs unit-step changes in the actuator stroke (output), exclusively based on the static (filtered) mid-span deflection variation (input). In short, as stated in expression (1), if the mid-span deflection reaches a predefined limit (Δc), a unit-step change is implemented, increasing

Fig. 1. OPS components of the movable scaffolding system's main girders.

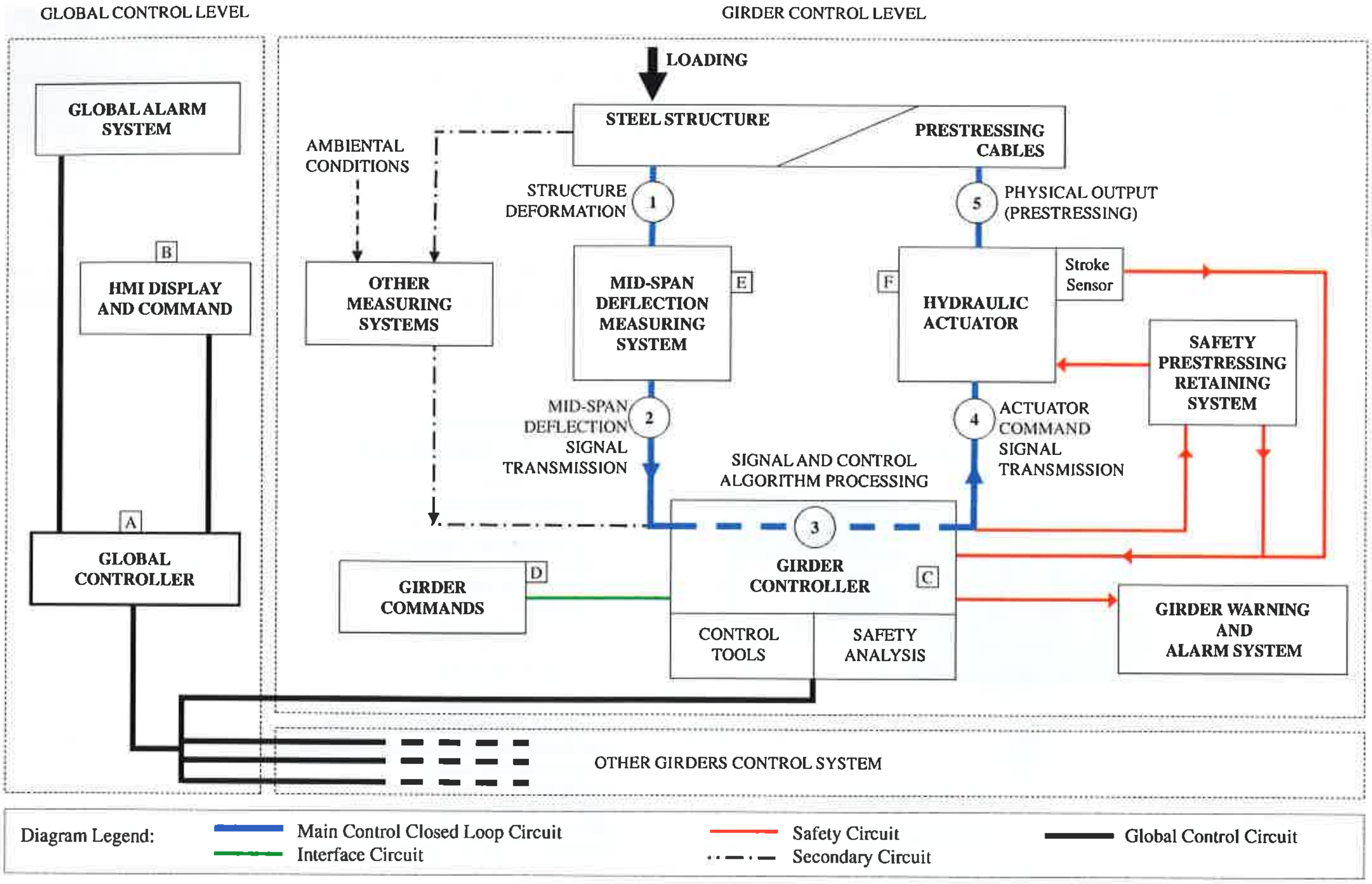


Fig. 2. OPS control diagram.

the prestressing force and thus reducing mid-span deflection [4]. A symmetrical algorithm is adopted for *deck prestressing mode.*

$$\begin{cases} \bar{\Delta}(t_i) > \Delta c & \Rightarrow \quad nc(t_i + \Delta t) = nc(t_i) + 1 \times \xi(t_i) \\ \bar{\Delta}(t_i) \leq \Delta c & \Rightarrow \quad nc(t_i + \Delta t) = nc(t_i) \end{cases} \tag{1}$$

where,

- $\bar{\Delta}(t_i)$ is the filtered mid-span deflection at instant t_i;
- Δc is the predefined mid-span deflection control limit;
- Δt is the time step adopted in the control algorithm ($\Delta t = t_i - t_{i-1}$);
- $nc(t_i)$ is the number of stroke unit-step changes performed by the actuator at instant t_i;
- $\xi(t_i)$ is the overall validation function at instant t_i (assumes the value 0 or 1).

These operational modes were established as being monotonous–prestressing is monotonously increasing for the concrete pouring stage and monotonously decreasing for the deck prestressing stage–because the inherent loadings are themselves monotonous. This particularity of the control strategy is adopted for safety reasons, reducing the probability of software errors and hardware malfunctions.

In this application field, time delay can be neglected in *feedback analysis* [7,8] due to the monotony of the automatic modes and due to the *quasi-static* nature of the whole system. Indeed, both main loading cases are relatively slow (taking several hours) compared to a unit-step change (few seconds), which is, in turn, relatively slow when compared to the natural vibration period (less than 1 s).

The control strategy is extremely simple and does not comprise a model-based algorithm. Thus, algorithm efficiency does not depend on prior numerical model accuracy.

4. Organic Prestressing System automation

An automation solution based on two control levels is implemented: *global control level* and *girder control level.* The *Girder control level*, clearly the most important, includes the main control closed loop circuit,

Table 1
OPS operational modes.

	Main automatic modes		Complementary automatic modes		
Operational mode	*Concrete pouring mode*	*Deck prestressing mode*	*Positioning mode*	*Relaxing mode*	*Manual mode*
Objective	Mid-span deflection control	Mid-span deflection control	Implementation of predefined construction deflections	Relaxation of prestressing cables	Direct command of hydraulic actuator
Action (Hydraulic actuator piston)	Extends	Retracts	Extends	Totally retracts	Extends or retracts
Construction cycle stage	Concrete pouring	Deck prestressing	Formwork positioning	After deck prestressing	Not specified

comprising sub-processes 1 to 5 (described in Fig. 2) corresponding to control algorithm (1) implementation. The *Global control level* aims only to provide a more "user-friendly" OPS and also to compare different girder behaviours.

4.1. Operational modes

Each girder control system comprises 5 operational modes, suitable for each construction cycle stage. Mode descriptions, their objectives, their associated actions and construction stages, where useful, are presented in Table 1. *Manual mode*, which is useful for casual needs, allows the prestressing forces to increase or decrease, according to the operator's intention. Due to safety requirements, if predefined limits are reached, *manual mode* is automatically disabled. Complementary automatic modes are available for short transition operations (after or before girder launching). The main automatic modes–*concrete pouring mode* and *deck prestressing mode*–are available for long operations (several hours).

4.2. Hardware components

The main hardware components (A to F) indicated in Fig. 2 are described in Table 2. OPS also comprises other hardware components

Table 2
Main hardware components.

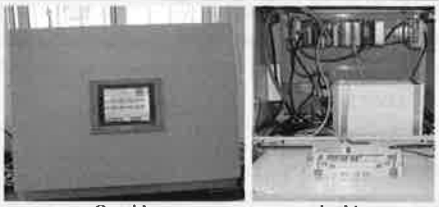
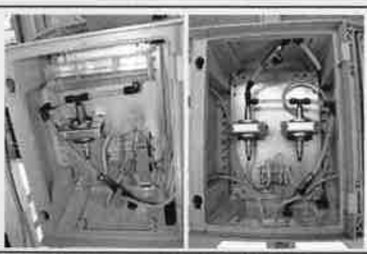
		Hardware images	Main tools and/or characteristics
Global Control Level	A – Global Control Unit	 Outside Inside	• Programmable Logical Controller (PLC) • Uninterrupted Power Supply (UPS) • Communication devices: wireless communication with the girder control unit and wireless data communication over a Global System for Mobile Communications (GSM) network to perform OPS remote supervision • Global Command
	B – Global Command	 	• Human Machine Interface (HMI) – touch screen: - User-friendly display with guiding/limiting options - on-line information display - warning report - alarm report and description - OPS parameterization - Equipment configuration tools
Girder Control Level	C – Girder Control Unit		• PLC • UPS – ensures data acquisition inthe event of power failure • Communication device: wirelesscommunication with global control unit • Electric board (power supplies, low voltage switch gears, electromechanical relays) – reduced electric power (max. 3 kW) • Girder Commands
	D – Girder Commands		• *Girder control station (left)* - mode selector and validation button Note: This command has priority over any other command • *Pendant station* (right) - allows direct command of the hydraulic actuator Note: Needs higher level control permission (*Girder control station* or HMI)
	E – Mid-span deflection measuring system		• *Static column fluid pressure measurement*[9]: - pressure transducer – output signal (0-20 mA) - reservoir and pneumatic tubes - pneumatic tubes rigid protection (thermal variations, solar rays and accidental mechanicalshocks) - low-viscosity mineral oil - temperatures range from -10 to+50 °C - high accuracy and precision of ±1 mm
	F – Actuator		• *Linear hydraulic actuator:* - 250 ton pushing force available - 330 mm stroke available • *Hydraulic power pack:* - hydraulic pressures up to 350 bar - hydraulic actuator speed 0.23± 0.02 mm/s

Table 3
Error or failure sources and corresponding types of evaluation and validation procedures.

Sub-Process (see Fig. 2)		Error or failure source	Evaluated quantity (examples)	Type of validation	Evaluation/Validation implementation
1	**Structure Deformation**	Structure-automation system	Deflection measures	$\xi_\alpha(t_i)$	In service (step Δt)
1 → 2	**Deflection Measuring**	Mid-span deflection measuring system	Sensor and deflection measurements	HD Tests	Before service
				Check list (C1)	In service
		Sensors	Sensor measurements	$\xi_\alpha(t_i)$	In service (step Δt)
2	**Mid-span deflection signal**	Sensor connections	Electric signal	$\xi_h(t_i)$	
3	**Signal processing and control processing**	Software code	---	S and HS Tests	Before service
		Electronic circuit	Electric signal	$\xi_h(t_i)$	In service (step Δt)
4	**Actuator command signal**	Actuating system connection	Electric signal	$\xi_h(t_i)$	
4 → 5	**Prestressing force application**	Structure-automation system	Actuator stroke measures	$\xi_\alpha(t_i)$	
				Check list (C1)	In service (Concrete pouring curves)
		Actuating system	Actuator stroke measures	$\xi_\alpha(t_i)$	In service (step Δt)
		Accuracy of actuator action	Actuator stroke measures	HA Tests	Before service
		Accuracy of structure stiffness	Actuator stroke vs deflection measures	SS1, SS2 and SS3 Tests	
		Accuracy of prestressing force	Monostrand forces measures	P1 Tests	

such as temperature sensors and hydraulic power pack pressure transducers (in *other measuring systems*), powered nuts and position sensors (in the *safety prestressing retaining system*), luminous towers and buzzers (in the *girder's warning and alarm system*). The *safety prestressing retaining system* is a mechanical device which provides the organic anchorage back-up in the event of actuator failure.

5. Methodology to achieve operational and integrity validation of the structure-automation system

In order to ensure that the OPS does not implement mid-span deflection control actions if unexpected situations occur–including any system or sub-system failure, error or unexpected response–a hybrid methodology to achieve operational and integrity validation was developed, comprising experimental validation tests, checklists and implementation of software safety features.

Experimental validation tests included coupled and uncoupled tests of the hardware, software and structural components.

Before giving a general view of the methodology, it is useful to clarify that software safety features provide continuous evaluation of the hardware components' state of integrity and of the whole system's operational status. If this continuous evaluation suggests any abnormal situation OPS reaches a braking level (actuator blockage) and an alarm is triggered.

Table 4
Automation safety policy.

Type of assessment	Abnormal conditions	System status Automatic modes	System status Manual modes	Warnings and Alarms	Operator Procedures	Examples
OPS connection integrity	$h(t_i)=0$ $(\xi_h(t_i)=0)$	Unavailable	Unavailable	ALARM	• Maintenance is required	• Cable disconnected • Problem in sensor wiring
Fundamental components integrity	$h(t_i)=0$ $(\xi_h(t_i)=0)$				• Check-up • Maintenance is required	• Hydraulic power pack engine failure
Fundamental components response	$\alpha(t_i)\notin[\alpha_m,\alpha_M]$ $(\xi_\alpha(t_i)=0)$		Available			• Sensor reaches the alarm operational limit
	$\alpha(t_i)\notin[\alpha_m^{war},\alpha_M^{war}]$ $(\xi_\alpha(t_i)=1)$	Available		WARNING	• Check-up • Maintenance probable	• Sensor reaches the warning operational limit
Structural response	$\alpha(t_i)\notin[\alpha_m,\alpha_M]$ $(\xi_\alpha(t_i)=0)$	Unavailable		ALARM	• Check-up • Maintenance is required	• Mid-span deflection reaches parameterized alarm limit
	$\alpha(t_i)\notin[\alpha_m^{war},\alpha_M^{war}]$ $(\xi_\alpha(t_i)=1)$	Available		WARNING	• Check-up • Maintenance probable	• Mid-span deflection reaches parameterized warning limit
Secondary components integrity	$sh(t_i)=0$ $(\xi_h(t_i)=1)$					• Error in the detection of the deviation shores positioning

In Table 3, a systematic approach, based on the analysis of sub-processes 1 to 5, is presented comprising error or failure sources, type of validation and form of implementation. This table enhances the need for a set of evaluation and validation procedures (functions, checklists or tests). The definition and implementation of these procedures allow the detection of the improper functioning of the structure-automation system. It should be made clear that the aim of this methodology is to ensure improper functioning detection and not to ensure improper functioning diagnosis. Nevertheless, in case of occurrence of non-integrity, the system is able to identify the primary error source. The particular case of power supply failure, which is not formally considered to be inadequate system functioning, is subject to preventive measures (UPS installation — see Table 2).

5.1. Operational and integrity validation — software safety features

Software codes were developed according to expression (1), where any unit-step change is multiplied by an overall validation function $\xi(t_i)$ at instant t_i. This function is given by the expression (2):

$$\xi(t_i) = \xi_h(t_i) \times \xi_\alpha(t_i) \tag{2}$$

where $\xi_h(t_i)$ and $\xi_\alpha(t_i)$ are binary (0 v 1) functions–respectively, the hardware integrity validation function and the system operational validation function, both at instant t_i–obtained by:

$$\xi_h(t_i) = \prod_{j=1}^{nh} \Phi_{h_j}(t_i) \tag{3}$$

$$\xi_\alpha(t_i) = \prod_{k=1}^{n\alpha} \Phi_{\alpha_k}(t_i) \tag{4}$$

where:

- nh is the total number of fundamental hardware components;
- $n\alpha$ is the total number of symptom-variables, i.e., all variables which may be a symptom of inadequate structure-automation system behaviour;
- $\Phi_{h_j}(t_i)$ is the integrity evaluation function of j fundamental hardware component, based on h_j electric signal evaluation at instant t_i;
- $\Phi_{\alpha_k}(t_i)$ is the symptomatic evaluation function based on α_k symptom-variable evaluation at instant t_i (provides operational evaluation).

To ensure representation simplicity, variables h_j and α_k will be represented hereafter as h and α, respectively.

In every instant t_i (with frequency $1/\Delta t$), fundamental variables (mid-span deflection and actuator stroke) are used to evaluate the operational state of the structure-automation system. The operational state of the system is only verified if each α symptom-variable is within a corresponding predefined interval, as follows:

$$\Phi_\alpha(t_i) = \begin{cases} 1, & \alpha(t_i) \in [\alpha_m; \alpha_M] \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

Table 5
Hardware and software test program.

Component	Test			
	S	HA	HD	HS
Commands		×		×
Mid-span deflection measuring system			×	×
Actuator		×		×
Control unit (software)	×	×	×	×
Other measuring systems	×			×

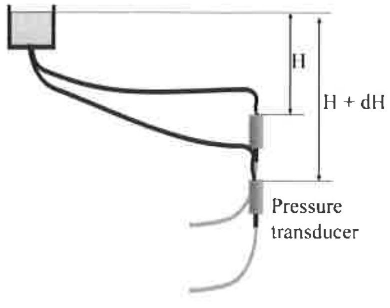


Fig. 3. Static column fluid pressure measurement [9].

where α_m and α_M are obtained by:

$$\begin{cases} \alpha_m = \alpha_{exp} + (\alpha_{inf} - \alpha_{exp}) / \gamma_m \\ \alpha_M = \alpha_{exp} + (\alpha_{sup} - \alpha_{exp}) / \gamma_M \end{cases} \tag{6}$$

in which α_{inf} and α_{sup} are the predefined acceptable limits of the α variable according to the components/structure technical specifications, α_{exp} is the corresponding expected operational value and γ_m and γ_M are the corresponding partial safety coefficients, also established beforehand for each security level.

It should be noted that unexpected structural stiffness reduction, cable fatigue damage and other unexpected structural symptoms may be revealed by the application of this methodology.

The integrity assessment of any fundamental hardware component is verified if the corresponding electric feedback signal h at instant t_i is not null:

$$\Phi_h(t_i) = \begin{cases} 1, & h(t_i) \neq 0 \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

Alarm occurrences generate the interruption of the selected operational mode and the non-availability of automatic mode selection. The return to normal functioning (all functions available) is only achieved after correction of the causes and symptoms that triggered the alarm. Conversely, warnings have no consequence on the system's operationality since they arise from the integrity assessment of secondary components (based on the $sh(t_i)$ electric signal) or from a secondary level operational assessment (with more restrictive safety coefficients–γ_m^{war} and γ_M^{war}–and consequently more restrictive limits–α_m^{war} and α_M^{war}). Table 4 presents the automation safety policy regarding all different types of assessment, corresponding abnormal conditions, corresponding system status, warnings and alarms and operator procedures. Mainly, Table 4 explains "what happens" if abnormal conditions are observed.

5.2. Hardware and software validation tests

A test program (see Table 5) was developed for the *girder control level*, comprising 4 sets of tests which were carried out in the laboratory and on

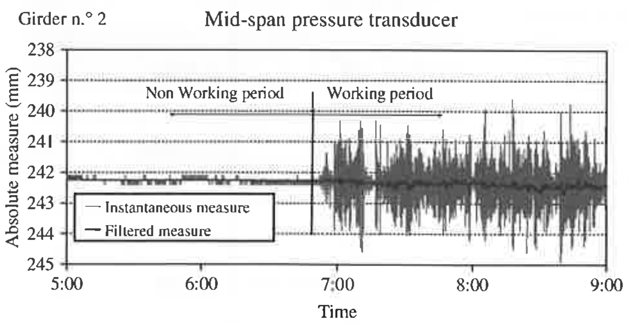


Fig. 4. Pressure transducer measuring data.

Table 6
Deflection measuring system validation criteria.

Level	Task	Procedure description	Criteria
1	Transducer accuracy evaluation	1.1 – Evaluating the absolute value of the difference between the average value of 5 consecutive measurements (of the same measurand) and the reference value (assumed to be the true value) obtained with a calibrated device (performed in the laboratory)	<1 mm
2	Embodiment inspection	2.1 – Evaluation of the cabinet position error	<5 mm
		2.2 – Observation of air-bubbles in the pneumatic tubes	No air-bubbles
		2.3 – Observation of leaks	No leaks
		2.4 – Observation of connections	All fitted
		2.5 – Observation of the pneumatic tubes rigid protection	All fitted
3	Transducer measuring stability evaluation	3.1 – Analysis of continuously measured instantaneous data, taken over 4 consecutive days from 0 to 6 a.m., evaluating the absolute value of the difference between each measured value and the average value for that period	<3 mm
4	Measuring accuracy evaluation	4.1 – Evaluating the absolute value of the difference between the average value of 10 filtered mid-span deflection values (of the same measurand) and the reference value (assumed to be the true value) obtained with a calibrated device.	<2 mm

site. Final software tests involved hardware embodiments with all components (HS test set) and included multiple combinations of mode selections in different scenarios. Although the mid-span deflection measuring system is based on known technology [9], its importance to system reliability obliged the development of a specific validation methodology.

6. Mid-span deflection measuring system — software filtering and validation criteria (HD tests)

The mid-span deflection measuring system (Fig. 3) mainly comprises a reservoir, pneumatic tubes (and corresponding rigid protection) and sensor cabinets (see Table 2) where pressure transducers are set up.

In order to overlook the girder's vibration effect in the mid-span deflection measurement, i.e., to identify static mid-span deflection, dynamic filtering is imposed (see Fig. 4). More than one technique may be adopted to achieve such a software filtering procedure.

The actual mid-span deflection value at a given instant t_i may be broken down into static and dynamical components, as follows:

$$\Delta(t_i) = s(t_i) + d(t_i). \tag{8}$$

For any analysis of the $T_A \leq \Delta t$ time interval that is much longer than the structure's natural vibration period, T ($T_A \gg T$), if n consecutive instantaneous mid-span deflection values are considered with a small time step dt ($dt = T_A/n \ll T$), it can be demonstrated that:

$$\frac{\sum_{k=1}^{n} d(t_i - T_A + k \times dt)}{n} \approx 0. \tag{9}$$

Eq. (9) states that in a purely vibratory response the displacement average value during a time interval is approximately null, if that time interval comprises several vibrations. This demonstration is trivial and may be achieved using trigonometric variables.

On the other hand, considering that the static deflection variation is linear during the analysis time interval, T_A (which is reasonable for loading periods much longer than T_A), then:

$$\frac{\sum_{k=1}^{n} s(t_i - T_A + k \times dt)}{n} = s\left(t_i - \frac{T_A}{2}\right). \tag{10}$$

Thus, a simple solution is to consider the filtered mid-span deflection $\bar{\Delta}(t_i)$ at the instant t_i given by the average of n consecutive

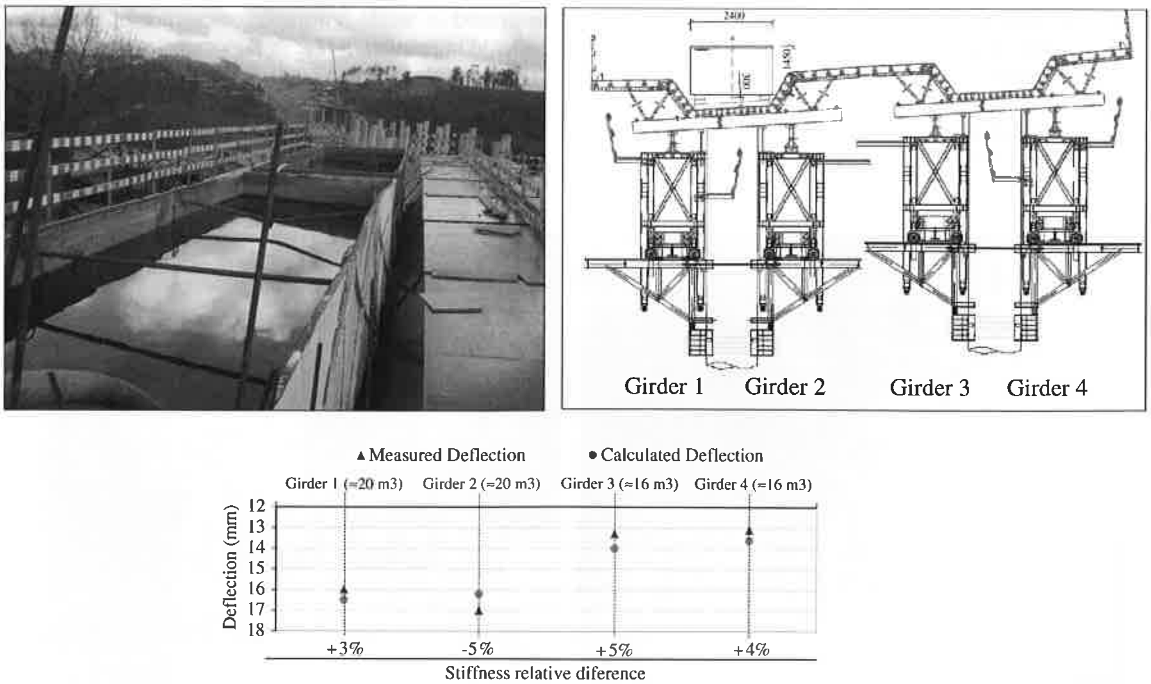


Fig. 5. Girder stiffness evaluation.

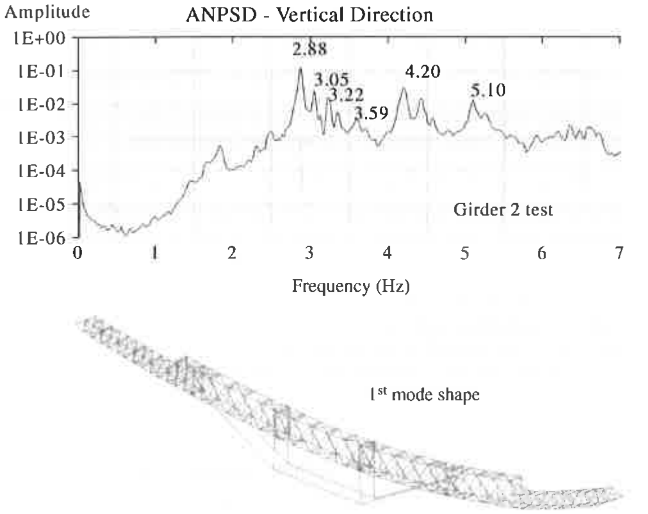


Fig. 6. Average spectral estimation of vertical accelerations.

mid-span instantaneous deflection measurement values, recorded with a frequency $1/dt$, during the analysis time interval, T_A:

$$\overline{\Delta}(t_i) = \frac{\sum_{k=1}^{n} \Delta(t_i - T_A + k \times dt)}{n}. \tag{11}$$

Considering expressions (8)–(11), the filtered mid-span deflection is given by:

$$\overline{\Delta}(t_i) \approx s\left(t_i - \frac{T_A}{2}\right) \tag{12}$$

which is the static component of mid-span deflection (with a neglectable delay of $T_A/2$). Reasonable results have been found for $T_A/T > 30$ and for $T/dt > 10$ ratios.

Mid-span deflection measurement validation criteria, presented in Table 6, comprise specifications for all mentioned sub-components. Due to the lack of any regulatory orientation, a validation methodology for the mid-span deflection measuring system [3,10,11] was established comprising 4 validation levels (see Table 6). Previous calibration is necessary according to pressure transducer specifications.

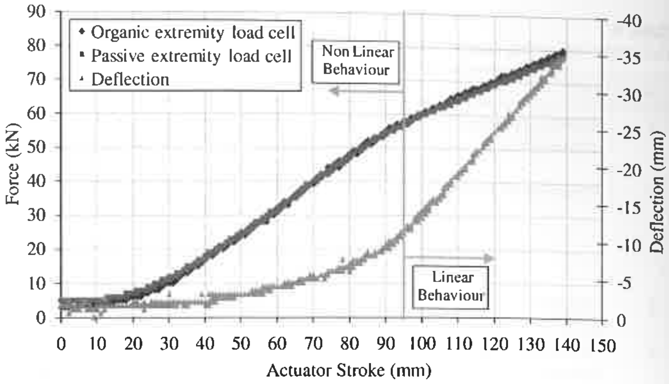


Fig. 8. Stroke-prestressing force and stroke-deflection curves.

Considerable noise is usually observed during working periods due to on site tasks, so the evaluation of the transducers' measuring stability (Procedure 3.1) is to be performed outside of work periods (see Fig. 4).

In the present application, according to the filtered measured values acquired during mid-span deflection evaluation procedure, system precision of ± 1 mm was observed.

Temperature effects have no influence on the mid-span deformation and on the deflection measuring system [11].

6.1. Girder stiffness and prestressing losses — experimental characterization

Sets of SS1, SS2, SS3 and P1 Tests mentioned in Table 3 were carried out to achieve operational validation of the structural elements (main girders and prestressing cables). These procedures, which may not be required in future applications, provided important information regarding structural uncertainties in the entire structure-automation system. The test results reasonably match the corresponding values of the prior numerical model.

6.1.1. Material laboratory tests (SS1)

Tests were performed in the laboratory to evaluate the modulus of elasticity of the girder steel. The values obtained were compared with the Eurocode [12] mechanical characteristics for grade S355 steel considered in the design stage. A reduction of approximately 5% was observed in relation to the average value of the modulus of elasticity.

6.1.2. Girder stiffness evaluation (SS2)

In order to evaluate girder stiffness, two water reservoirs were installed above the formwork for performing load tests (Fig. 5). The

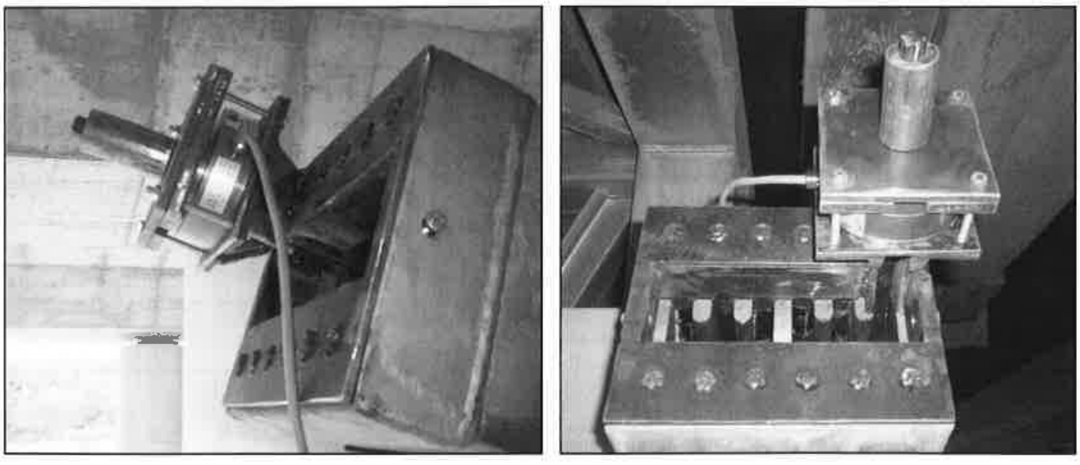


Fig. 7. Load cell embodiment.

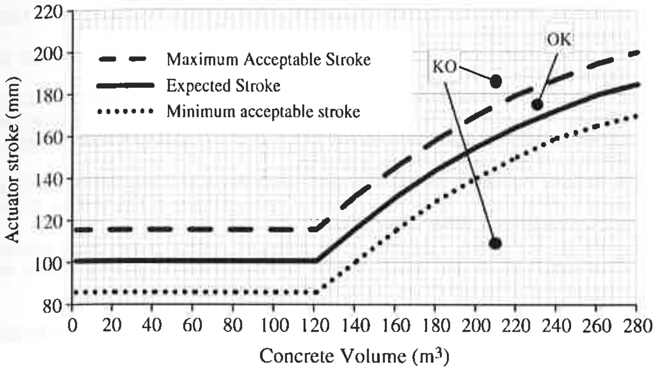


Fig. 9. Concrete pouring curve for operational control [4].

mid-span deflection response of each girder was measured with the OPS deflection measuring system. Results revealed that the difference between measured and theoretical deflections was less than 5% (see Fig. 5).

6.1.3. Dynamical tests (SS3)

Three seismographs were set up on the upper chord of predefined sections of Girder 2. Prestressing cables were tensioned nearly in the linear stage. The first mode's natural frequency is experimentally identified as 2.88 Hz — Fig. 6. As expected, this value is relatively close to the upper limit of the numerical interval [2.61; 3.04] Hz, these limits being given by, respectively, the analysis of the numerical model without prestressing cables (2.61 Hz) and considering the perfect linear behaviour of the cables (3.04 Hz).

6.1.4. Prestressing losses evaluation (P1)

In order to evaluate the friction coefficient between prestressing cables and deviation saddles (last validation procedure presented in Table 3), 2 *annular compression load cells* were installed at either extremity of 1 monostrand (see Fig. 7).

A set of 4 tests was carried out generating the average curves, presented in Fig. 8.

In the linear phase, the average of prestressing losses between anchorages due to friction is approximately 5.13%, generating a friction coefficient of $\mu = 0.076$ (estimated by the Cooley formulation [1]), which is within the friction coefficient interval specified in international standards [0.05; 0.10] for plastic ducts with lubricated strands [13].

6.2. Concrete pouring stage (checklist C1)

During each concrete pouring operation a checklist assessment was implemented comprising 2 main validation procedures. The deflection measuring system is validated if the measured deflection, during a predefined time interval is stable and within the corresponding limits (for the corresponding stage). The second procedure, which is of major importance, consists of comparing the HMI displayed stroke values with the expected ones. The expected stroke was generated as a function of the poured concrete volume (see curve with acceptable value ranges in Fig. 9). In the present application, the C1 checklist referred to a 20 m^3 poured concrete verification step.

6.2.1. In service operational data

In Fig. 10, a concrete pouring data clip is presented. It can be observed that the filtered (static) deflection varies approximately 1 mm around the control limit ($\Delta = 2.5$ mm) and that the response delay is irrelevant. It is very clear that the OPS does provide efficient deflection control (deflection without control would be nearly 60 mm [4]). Moreover, since OPS only actuates when the load increases (it is not influenced by vibrations), the adopted filtering technique also proved to be efficient.

The equipment was used for the construction of 23 spans of the bridge deck and no unexpected problems occurred with OPS. Common dysfunctions did occur — e.g. power supply failure or an electronic device breakdown and OPS detected such failures, permitting the implementation of basic maintenance tasks without disturbing site operations.

7. Conclusions

The presented automation solution is user-friendly and allows significant optimization of the movable scaffolding system's steel structure while simultaneously ensuring an enormous reduction (>90%) of mid-span deflection.

A hybrid methodology to achieve operational and integrity validation of the structure-automation system–comprising experimental validation tests, checklists and the implementation of software safety features–is developed and implemented with success. This methodology ensures the robustness of the structure-automation system.

Structural experimental tests, carried out in the first full-scale application, are not fundamental to future applications.

OPS software ensures integrity monitoring, damage detection and easy to use operational management of the system. Self-diagnosis, which is already partially implemented, is to be used more powerfully in the future.

The adopted OPS automation solution is feasible and efficient.

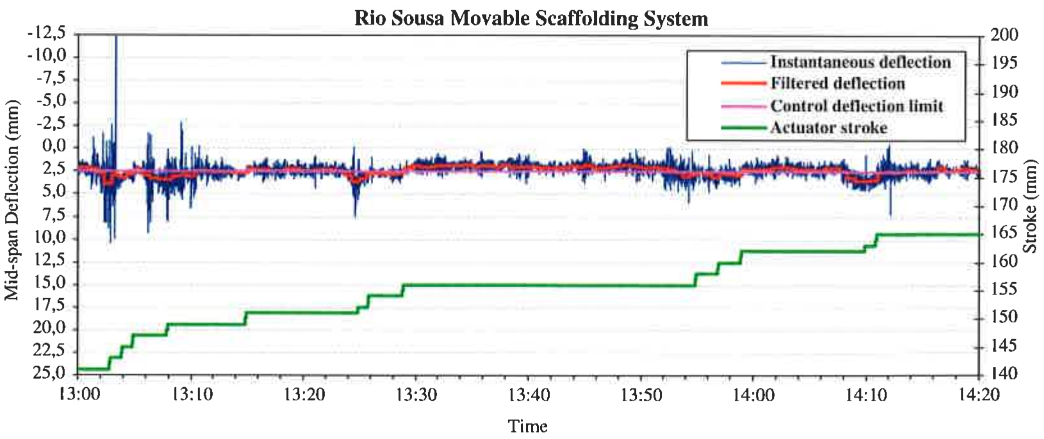


Fig. 10. OPS activity and mid-span deflection evolution during deck concrete pouring.

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