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Measurement of Restraint Moment Effect on Lab Specimens with Precast Girders Made Continuous

Mohammed Ibrahim[1](✉), Mauro Poliotti[1], Yuguang Yang[1], and Max A. N. Hendriks[1,2]

[1] Delft University of Technology, Delft, The Netherlands
M.S.Ibrahim-1@tudelft.nl
[2] Norwegian University of Science and Technology, Trondheim, Norway

Abstract. Typically precast girders are designed and utilized as simple supported members. Alternatively, the precast girders can be made continuous at the intermediate support using cast-in-place concrete topping. Once the girders are made continuous, time-dependent restraint moments will occur. The magnitude of the restraint moment is mainly affected by the creep and shrinkage behaviour of the concrete and the age of the girders at continuity. The developing restraint moment may affect the stress conditions near the support region and, in extreme cases, result in the loss of the integrity of the structural member. Currently, full-scale experimental campaign is underway on the shear behaviour precast continuous girders at Delft University of Technology. Inverted T girders are individually cast and later made continuous after a certain period. To investigate the influence of restrained action and quantify the prestress losses, fiber optic sensors (FOS) are embedded in the girders. By utilizing the FOS, the evolution of the concrete strain is monitored. This paper presents the measurement of the time-dependent strains. Furthermore, the concrete strains are analysed to evaluate the prestress loss and time-dependent restraint moment effect.

Keywords: Creep · Differential shrinkage · Fiber optic sensors · Precast girders · Restraint moments

1 Introduction

Precast continuous bridges using pre-tensioned girders is an attractive solution for bridges with span ranging between 15 to 40 m. In the system, the bridge deck is made continuous using cast in situ topping layer and cross beams to support superimposed traffic loads (see Fig. 1). Utilizing this construction method, many bridges are constructed in the Netherlands. The system is also used in the United States following the extensive investigations conducted in the PCA laboratories (Kaar et al. 1960; Mattock and Kaar, 1960).

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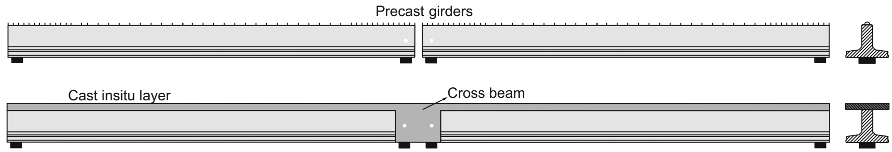

Fig. 1. Precast girders made continuous

While the bridge type takes the advantages from the continuity, the structural behavior of this system becomes complicated by the restraint moment developing after continuity. In the precast continuous girders, restraint moment arises from the constraint against the creep and shrinkage deformation of concrete (girder and topping) over time. These moments can significantly affect the behavior and performance of the precast girders.

Generally, two distinctive behaviors can be expected after the precast girders are made continuous(Oesterle et al. 1989; Miller et al. 2004; Menkulasi et al. 2018). They are either restraint moment from creep of the precast girder or differential shrinkage between the topping and girder. While both time-dependent responses resulted from the restraint, their action effects are not similar. As it can be seen from Fig. 2a, restraining the creep potential of the girders results in tension at the bottom. In contrast, the differential shrinkage between the topping and precast concrete will generate compression at the bottom.

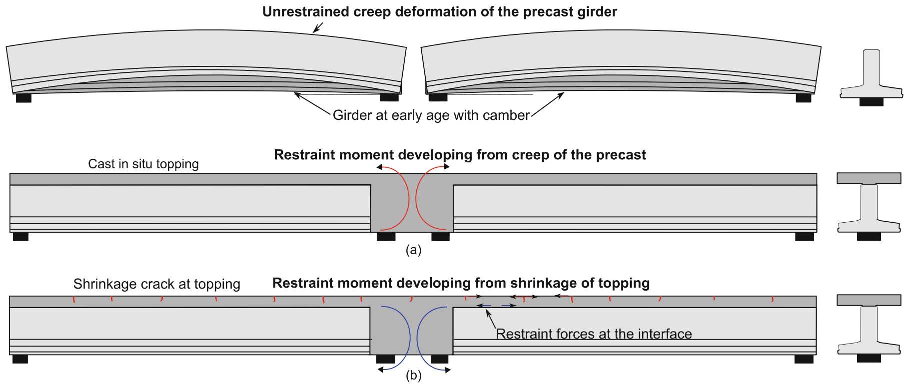

Fig. 2. a) Restraint moment due to creep (b) Restraint moment due to shrinkage of the topping.

To investigate these time-dependent behaviors, experimental and analytical research projects were mainly conducted in North America (Miller et al. 2004; Oesterle et al. 1989). The investigations aimed to provide recommendations for the design of intermediate support connections that can achieve structural continuity. Bridge design standards also provide guidance to avoid loss of continuity due to cracking of the cross beam. For instance, AASHTO (AASHTO 7th, 2014) specifies the evaluation of the stress state of the connection for the acting load combinations. If the age of the girder is at least 90 days, the code allows ignoring the influence of restraint moments. Recent studies also present similar recommendations with different girder continuity ages (Menkulasi et al.

2018). The analytical study recommends a minimum age of the girders at continuity to be between 55 to 90 days for various girders types and span lengths. Although the structural system is attractive, the required minimum age of the girder for continuity may discourage using the system due to the higher cost associated with storing the girders.

Currently, experimental research on the shear behavior of continuous precast members is underway at Delft University of Technology (Ibrahim et al. 2022). To accurately quantify the prestress level of the girders, Fiber Bragg Grating sensor-embedded rebar (hereafter referred to as smart rebar) was utilized. The smart rebar measures strain and temperature variation and they can be used to evaluate the time-dependent strain changes resulting from the restraint moment. In this paper, measurements from four precast continuous girders are presented. Moreover, a discussion on the prestress loss and influence of time-dependent restraint moment will be given.

2 Description of the Specimens

2.1 Specimens and Material Properties

Four specimens are used to monitor the prestress transfer and time-dependent effects. Each specimen is created by connecting two precast girders having a length of 11.25 m and 3.5 m. The continuity for the specimens is established by cast in situ topping layer and cross beam (see Fig. 3).

Specimens with straight or fan-shaped prestress layouts are used in the main girder, while the short girder (Cant. Beam) is centrically prestressed. Figure 4 presents details on the sectional properties, the prestress layout, and the sensor plan.

The girders are prestressed with 7-wire prestress strand having a diameter of 12.9 mm. Initial pretension force that results in an equivalent central prestress level between 2 to 6 MPa is applied on the strands (See Table 1). Within 18 h of the casting, the prestressing strands are released from the reaction wall.

Fig. 3. Precast continuous girder in the lab (Left: Main girder Right: Cant. Beam)

A concrete grade of C55/67 is targeted for the precast girders. The topping and the cross beam that make the specimen continuous use a concrete grade of C30/37.

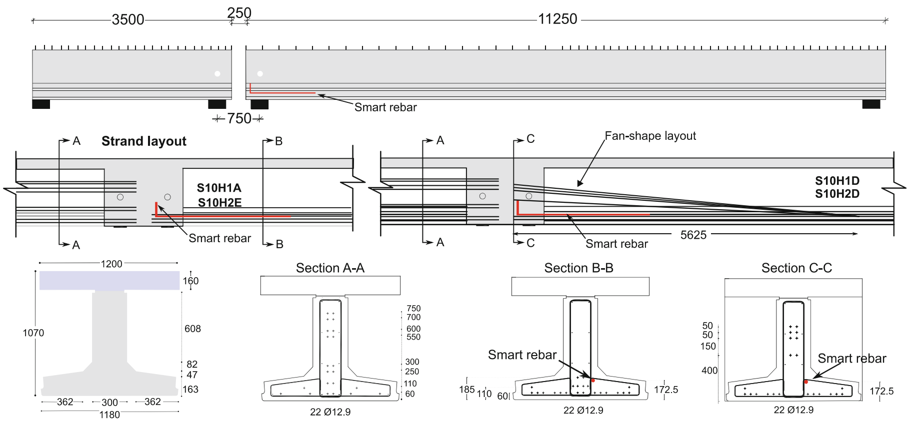

Fig. 4. Detail of the precast continuous specimens

The concrete grades are selected to be comparable with the existing bridges in the Netherlands. Table 1 provides an overview of the compressive strength test results from 150 mm cube samples. The age of girders at connection and the initial prestress force per strand is also provided in Table 1.

Table 1. Detail of the specimens

Specimen	Girder f_c [MPa]			Age of girder at connection	Topping f_c [MPa]	Initial prestressing force
	1^{st} day	7^{th} day	28^{th} day	[days]	28^{th} day	[kN/strand]
S10H1A	–	63.0	77.0	84	55.0	79.0
S10H1D	39.5	–	81.6	80		79.0
S10H2D	39.0	–	76.0	57	48.0	118.5
S10H2E	38.5	–	79.5	56		38.5
Cant.Beam	42.0	66.0	75.0	–		118.5

2.2 Monitoring Method

Fiber Bragg Grating (FBG) sensors are a type of optical sensor that can be embedded within concrete structures to monitor strain and temperature variation. These sensors measure changes in the Bragg wavelength of light reflected by a grating inscribed within an optical fiber (Yazdizadeh et al. 2017). The sensors are small and durable, making them ideal for long-term monitoring in concrete structures.

In the current specimens, the prestress and time-dependent effect is monitored using a rebar embedded with FBG sensors. The smart rebar has a diameter of 10 mm and

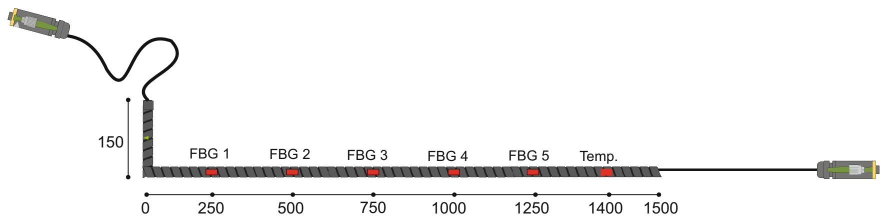

Fig. 5. FBG sensors layout

a length of 1.5m. The rebars are provided with a 90-degree bend having a length of 150 mm. The end detailing ensures sufficient anchorage length of the smart rebar and allows monitoring of strain change near the end of the girder (see Fig. 4).

Each smart rebar has five strains and one temperature measurement point. The strain measurement locations are 250 mm apart (see Fig. 5). Before casting the girders, the smart rebars are fixed to the shear reinforcement and placed close to the end of the girder along the bottom flange.

The strain state inside the precast girder was monitored at different stages before and after continuity. Initial measurements were taken after sensor installation was completed. After the prestressing strands were released, additional measurements were taken to monitor the prestress level and transfer length. In the subsequent months, several measurements were done until the day of experimental testing in the lab.

3 Result and Discussion

The results from smart rebars are presented in Fig. 6. The plots present the concrete strain against the age of the girder from all the FBG sensors. For ease of discussion, the FBG located in the middle (FBG 3) is highlighted for all the specimens at different ages. Each vertical line on the plot shows the range of measurements along the smart rebar.

After the strands are released, the concrete strains indicate an increase of 150 to 300 $\mu\varepsilon$. The incurred strains for each specimen correlate with the initial prestress level. Before continuity, except for specimen S10H2E, the remaining specimens show a significant strain increase in the following months (see the trend arrows). The time-dependent increment of the strain results from the combined effect of creep and shrinkage. The observed insignificant change in the strain state of S10H2E can be attributed to the relatively lower initial prestress of the specimen.

After the girder are made continuous, the previously increasing compressive strain is observed to stabilize and decrease for specimen S10H1A, S10H1D, and S10H2D. The stabilized strain and change over time can be observed from the reference line and red arrow. The change in strain evolution shows the net effect of the creep and differential shrinkage after continuity induces tensile strain. Recalling the discussion on the influence of restrain moment, this net tensile strain at the bottom implies that the dominant restraint moment comes from the creep of the prestress girders.

In contrast, the specimens with lower prestress (S10H2E) showed an abrupt increase in the compressive strain at the bottom. Considering the strain state before connection,

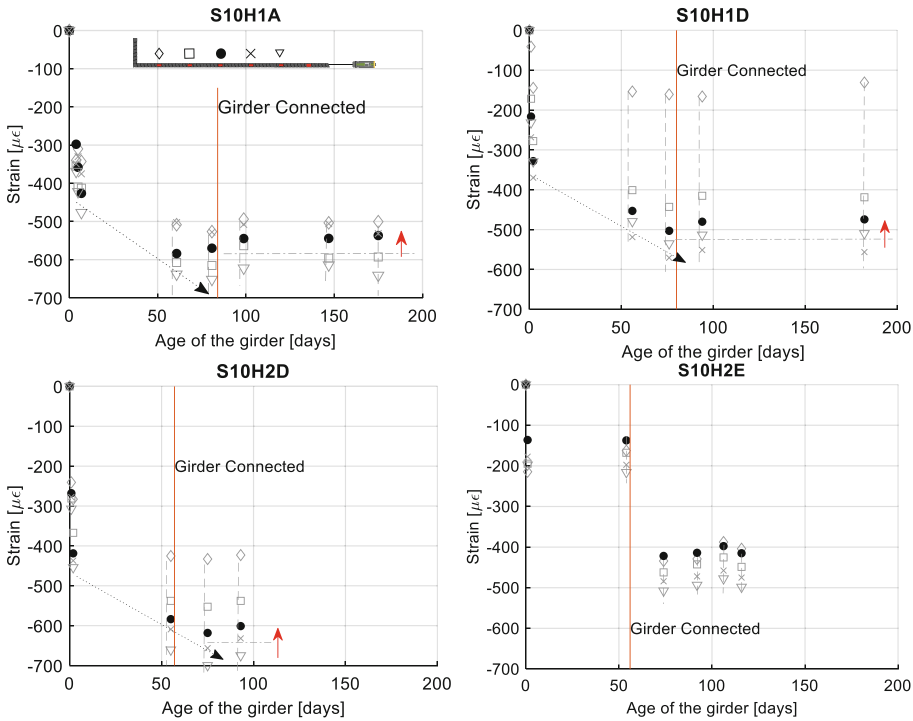

Fig. 6. Strain evolution of the precast girder at different age

an increase of more than 200 με is observed. This response mainly resulted from the restraint moment dominated by the differential shrinkage. Since the specimen had a lower prestress level, its tendency to creep and create countering restraint moment is lower.

3.1 Prestress Loss and Transfer Length

Besides the restraint-induced strain, the measurement before the connection gives insight into the prestress transfer length and prestress loss. Before evaluating the prestress loss, the theoretically expected concrete strain after the introduction of prestress (without creep and shrinkage) was calculated along the FBG sensor locations. In the evaluation, a sectional analysis is done using material properties estimated based on the compressive strength of the concrete at the release. The estimation of the material properties is done using Eurocode (CEN, 2005).

Figure 7 shows the estimated concrete strains after prestress release and the actual measured data along the girder length. Compared with the measurement, the evaluated initial concrete strains provide a lower estimate. The difference between the estimate and the measurement indicates the significant early age creep and shrinkage deformation in the girders. For instance, when assessing the first two days, specimen S10H1D shows an average increase close to 100 με. Similarly, a relatively higher early-age strain evolution is observed for specimen S10H2D.

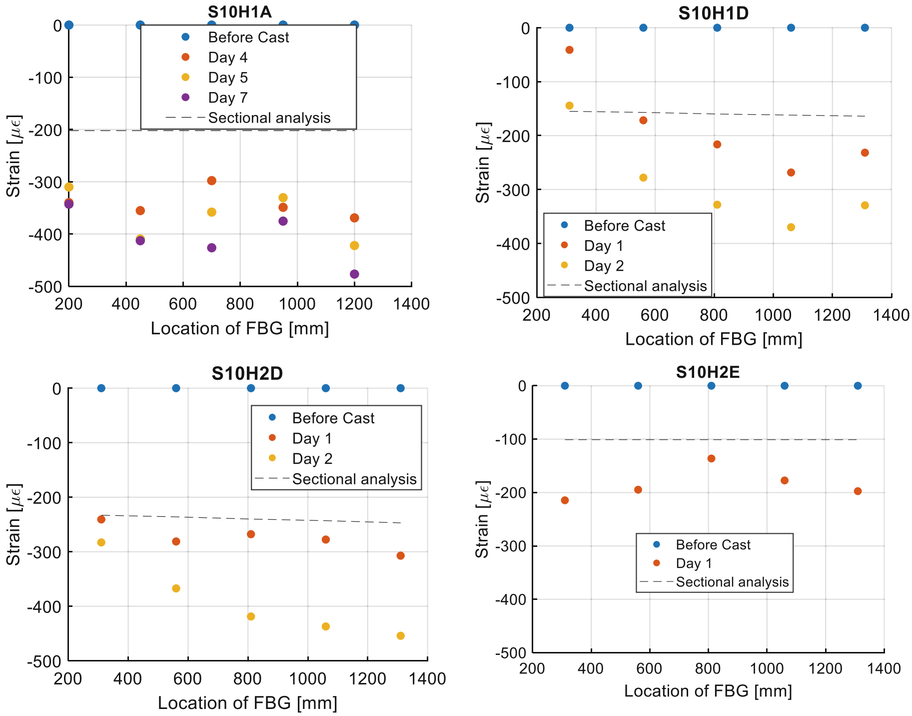

Fig. 7. Early age strain evolution along the smart rebar at different times

The observations from Fig. 7 also imply a significant portion of the total prestress loss occurs at an early age. This behaviour can be further observed by comparing the strain changes at different ages. The evaluation at the different ages is done by taking the initial strain after prestressing release to be equal to the strain from the sectional analysis. The strain changes using the initial strain as a reference are calculated for each measurement point. For ease of discussion, only the result from the FBG 3 is presented in Table 2.

Table 2. Time-dependent strain evolution of the girder

Specimen	Total time-dependent strain change † [με]	Time-dependent strain evolution at day [με]					Prestress level at connection [%]
		1	2	4	5	7	
S10H1A	– 367.8			-95.7	– 156	– 224	85.9
S10H1D	– 297.4	– 60.7	– 172.5				88.8
S10H2D	– 343.4	– 27.4	– 178.3				90.4

† *Total strain change between initial and strain state prior to connection*

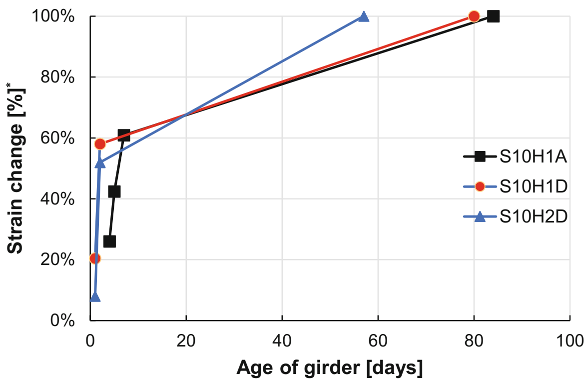

Fig. 8. Percentage of time-dependent strain at different ages up to continuity.

Figure 8 illustrates the amount of time-dependent strain evolved at different ages until continuity using data from Table 2. The plot indicates nearly 60% of the total time-dependent strain developed in the first week.

In general, the measured concrete strain accounts for the strain changes due to elastic deformation of the concrete, creep, and shrinkage of the girder. Assuming a perfect bond, the prestressing strands should incur a similar strain change as the concrete at any moment. Although the centroid of the strands and the location of the smart rebar do not coincide, considering the small eccentricity between them, the assumption of similar strain change is reasonable. Using the strain state at continuity, the prestress level is estimated (See Table 2). For specimens connected at later ages, the evaluated prestress level indicates a loss of close to 15%. (S10H1A and S10H1D). Specimen S10H2D was made continuous relatively early at 57 days and had a slightly lower prestress loss of 9.6%.

Additional to the prestress level, the measurement from the FBGs can be used to have insight into the transfer length. Using the Eurocode (CEN, 2005), the transmission length is estimated by using the average material properties at the time of prestress transfer. According to the code, the transmission length is calculated to be 158, 316, and 479 mm for specimens S10H2E, S10H1D/S10H1A, and S10H2D, respectively. Contrary to the code estimate, a noticeably shorter transmission length was observed using the smart rebar. The measured strains indicate the prestress was fully transferred to the concrete within 200 to 250 mm.

4 Discussion on the Lab Measurements and Their Implications for Existing Girders

In precast continuous girders, the cracking of the cross beam due to the restraint moment can be critical if it is mainly driven by potential creep than differential shrinkage. In the current specimens, despite the change in the strain state with a slight tensile strain increment, cracking of the cross beam is not observed. However, drawing a similar conclusion for the existing girder can be premature. Considering the girders are monitored for a relatively smaller period, the measured strains might not be the final stabilized strain.

Moreover, half of the span length of the real girders is used in the current specimens. This may result in the underestimated restraint effect in the lab specimens. Although the current observation does not show cracking in lab specimens, long-term monitoring is required to assertively extend similar conclusions to existing members.

Another important insight from the current observation is on the future application of the structural system. Precast continuous girders can be an attractive solution for medium-span crossings. However, the storage cost of girders arising from the minimum age of the girders may discourage their application. Although the current investigation addresses limited variables with a shorter monitoring period, the observed significant early age creep, and shrinkage losses may indicate the possibility of connecting the girders earlier. While the current insight is promising, more measurements with embedded strain sensors over a longer period and with different concrete mixtures are required to substantiate the observations.

5 Conclusion

An experimental campaign on precast continuous girders is underway to investigate the shear behavior at the intermediate support. Inverted T girders specimens are individually cast and later made continuous after a certain period. Smart rebars were embedded in the girders to monitor the prestress level and the influence of the time-dependent restraint moment effect. Four specimens with different prestress levels and layouts were monitored for more than 100 days before and after continuity was made. The study presented an analysis and discussion on the time-dependent effect, and the following conclusions are drawn:

1. Depending on the prestress level and the age of continuity, the restraint moment can be driven by creep or differential shrinkage. The restraint moment is dominated by creep for the specimen with higher prestress. In contrast, differential shrinkage controls for smaller prestress levels.
2. The time-dependent deformation of the specimens stabilized shortly after continuity. This indicates a potential for early connection of the girders without loss of structural integrity. Additional long-term monitoring are required to substantiate the observations.
3. Contrary to Eurocode estimation, a considerably shorter transmission length was measured in the specimens.

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References

1. AASHTO LRFD Bridge design specifications 7th ed. (2014) American Association of State Highway and Transportation Officials, Washington, DC

2. CEN (2005) Eurocode 2: Design of Concrete Structures—Part 1–1 General Rules and Rules for Buildings. NEN-EN 1992–1–1:2005. Comité Européen de Normalisation
3. Ibrahim MS, Yang Y, Roosen M, Hendriks MAN (2022) Challenges on the shear behavior of existing continuous precast girder bridges. Proceedings of the 14th Fib International Ph D Symposium in Civil Engineering
4. Kaar PH, Kriz LB, Hognestad E (1960) Precast-prestressed concrete bridges: 1. Pilot tests of continuous girders. J PCA Res Develop Laborat 2(2):21–37
5. Mattock AH, Kaar PH (1960) Precast-Prestressed Concrete Bridges: 3. Further Tests of Continuous Girders. J PCA Res Develop Laborat 2(3):51–78
6. Menkulasi F, Patel A, Baghi H (2018) An investigation of AASHTO's requirements for providing continuity in simple span bridges made continuous. Eng Struct 158:175–198. https://doi.org/10.1016/j.engstruct.2017.12.019
7. Miller RA, Castrodale R, Mirmiran A, Hastak M (2004) Connection between Simple Span Precast Concrete Girders Made Continuous. In: Project 12–53 - Final report. Transportation Research Board
8. Oesterle RG, Glikin JD, Joseph D, Larson SC, Steven C (1989) Design of precast, prestressed bridge girders made continuous. Transportation Research Board, National Research Council
9. Yazdizadeh Z, Marzouk H, Hadianfard MA (2017) Monitoring of concrete shrinkage and creep using Fiber Bragg Grating sensors. Constr Build Mater 137:505–512. https://doi.org/10.1016/j.conbuildmat.2017.01.084