Variability in Hog of Prestressed Concrete Girders

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SYNOPSIS

This paper explores the apparent discrepancy between theoretical predictions and observed values of hog (or camber) of prestressed concrete bridge girders. It also highlights the natural variability in hog due to the manufacturing process and other sources at the time of erection. Data recorded for more than 50 girders are used to highlight this variability and to compare with theoretical predictions.

1 INTRODUCTION

A prestressed concrete girder typically hogs upwards as a result of eccentric prestress forces overcoming the downward deflection due to self weight. When the girder hog is significantly different from that assumed in design, problems may occur during construction of the bridge deck. Such problems may be associated with the hog being excessive, compared with theoretical predictions, or as a result of variations in hog of girders within the same span.

In some cases, regrading of the road on the bridge and approaches may be required to maintain a minimum thickness of deck slab and/or deck wearing surface. Alternatively, lowering of pedestals may achieve a similar result provided that girder hogs are measured before pier headstocks are constructed. Excessive hog may also result in larger than anticipated girder end rotations which may adversely affect the rotational capacity of the bearings and should be checked by the designer.

The Queensland Department of Main Roads (QDMR) have experienced problems associated with excessive and variable girder hog during construction of a number of bridges over the years. In response to recent difficulties encountered on the Pacific Motorway Project between Brisbane and the Gold Coast QDMR have revised their specification for girder manufacture with regard to curing times to ensure greater consistency of girder hog.

The subject of hog is also receiving attention overseas as evidenced by recent investigations by Yazdani & Mtenga (1997) and Woolf & French (1998) sponsored by the Departments of Transportation in Florida and Minnesota, respectively.

2 THEORETICAL METHODS FOR ESTIMATING HOG

Hog is time-dependent: it attains an instantaneous value at transfer of prestress and continues to grow with time, experiencing greatest growth during the first month and at a diminishing rate thereafter. The growth of hog with time for a typical girder is shown schematically in Figure 1. Depending on the age of the girder at erection, the hog at the time of placement of the deck slab may be as much as twice that of the initial value at transfer. After erection, girders experience a series of downward deflections due to the weight of the concrete deck slab, construction of edge parapets, median barriers, footways, and deck wearing surface.

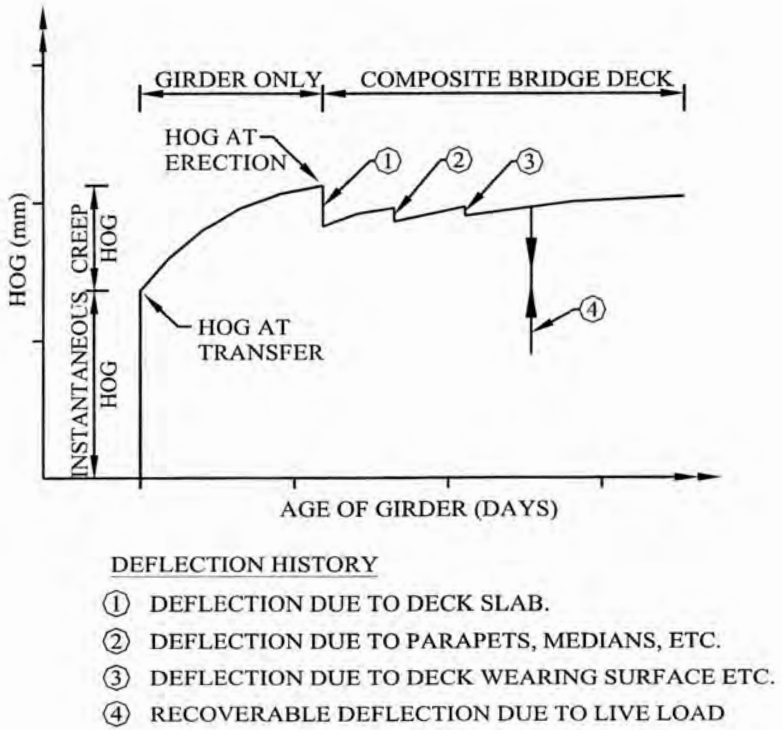

Figure 1: Deflection History for a Typical Girder

During this time and throughout the service life of the structure the hog continues to increase due to creep effects, albeit at a reduced rate after composite action is formed between the girders and deck slab.

In order to calculate the hog at any instant in time, creep and shrinkage strains that develop in the concrete and relaxation of prestress strands must be taken into account. There are three basic categories of methods for calculating hog which account for these effects:

- Simplified methods which use a creep multiplier to account for time dependent growth;
- Simplified methods based on an effective Young's Modulus which reduces with time to account for creep effects; and
- Rigorous methods of analysis involving integration of strain and curvature along the girder and which account directly for loss of prestress over time.

Details of these methods can be found in text books on prestressed concrete (refer Gilbert & Mickleborough (1990), for example).

Section 5 of the Australian Bridge Design Code (1992) permits the calculation of hog either by simplified method or rigorously from first principles. For the simplified method, the time dependent hog is regarded as being the sum of hog due to shrinkage and hog due to creep for an uncracked girder. These components are calculated separately and then added. When using the refined method of calculation, the designer is free to choose a suitable procedure to allow for creep and shrinkage effects. The Code also recommends that a likely range of hog values be estimated by taking account of the variability of the various parameters which affect hog (refer Section C5.8.5).

3 COMPARISON OF THEORETICAL AND OBSERVED HOG

In this section theoretical predictions of hog are compared with measurements recorded on the Binstead Way Overpass Bridge which was constructed in 1999/2000 as part of the Pacific Motorway Project. The bridge deck consists of 5 spans of 1500mm deep Tee Roff girders with a cast in situ deck slab of 160mm minimum thickness. The distance between bearings for each span is 33.6m, 35.0m, 35.3m, 19.1m, and 33.9m for Spans 1 to 5, respectively. There are 59 girders in total, all of which were cast on site. The girders were cast one at a time in a single casting bed with a typical cycle time of 24 hours.

The hog of each girder was measured approximately four months after casting of the last girder. This was undertaken between 6am and 8am on the same day to minimise variations due to temperature changes. The results of the survey are shown in Figure 2 for each of the girders. One striking feature is the variation of hog for girders of similar length and identical prestress arrangement. For example, girders in Spans 1 and 5 have nearly the same length and yet the hog varies between 61mm (minimum in Span 5) to 143mm (maximum in Span 1). In Spans 2 and 3 the hog varies from 91mm to 142mm.

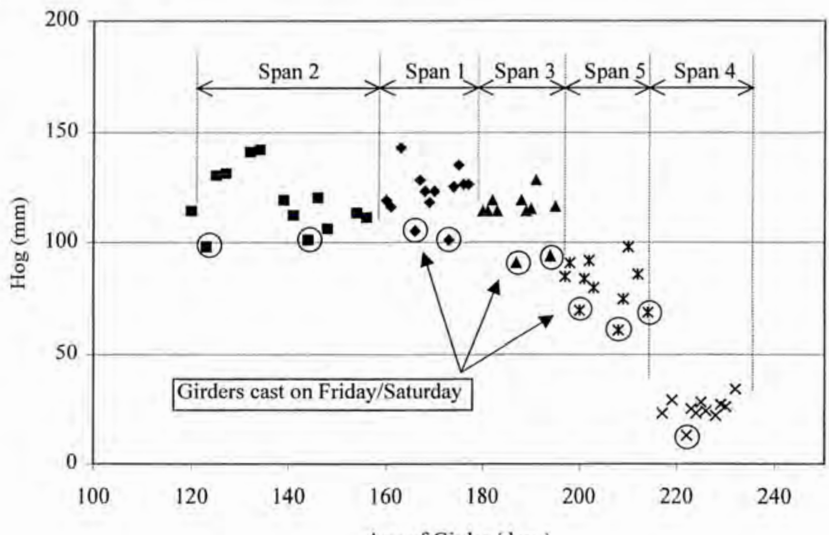

Figure 2: Variation in Hog of Tee Roff Girders

The same hog data is summarised in Table 1 for each span. Whilst the average hog for Spans 1 to 3 are relatively similar (122mm, 118mm and 113mm, respectively) the average hog in Span 5 is only 81mm. The reason for this difference is unclear. The girder depth and prestress arrangements are the same in Span 5 as for the other long spans. QA records confirm that the correct jacking force was used and that the same curing regime was employed. Climatic conditions during the period of casting also provide no satisfactory explanation for the difference in hog. Relative humidity and temperature data for this period are shown in Figure 3 together with the measured hog data. There appears to be no statistical relation between the measured hog and ambient conditions during the early stages after casting. Despite the obvious difference in hog between Span 5 and the other long spans, these girders were approved for use by QDMR as there are no criteria in their current specification relating to girder hog.

Span No.	Girder Length (m)	Avg Hog (mm)	Min Hog (mm)	Max Hog (mm)	Range (mm)
1	33.6	122	101	143	42
2	35.0	118	98	142	44
3	35.3	113	91	128	37
4	19.1	25	13	34	21
5	33.9	81	61	98	37

Table 1: Summary of Hog Data for Tee Roff Girders

The range of hog values measured for each span is also shown in Table 1. This refers to the difference between the minimum and maximum hog values for girders within the same span. The hog range appears to be relatively consistent, varying between 37mm and 44mm for each of the longer spans.

It is interesting to note that within each span there are two or three girders which have noticeably less hog than the other girders within the same span (refer Figure 2). A check of casting dates reveals that in each case the girders with lesser hog were cast on either Friday or Saturday. It seems likely that these girders were left in the mould over the weekend and that this extra period of controlled curing resulted in less hog.

The measured hog for girders in Span 1 are compared with theoretical predictions in Figure 4. This shows that the actual girder hog exceeds the estimated value of hog for all girders. The measured hog varies from 101mm to 143mm (refer Table 1) compared with the estimated hog of 80mm (at 28 days) which was tabulated on the drawings. The difference between design and actual hog is due in part to additional growth from creep effects between the assumed time of erection (28 days) and the age of girders at the time of survey (approximately 200 days). According to the curve of theoretical hog, this would account for approximately 15mm difference in hog. The following section discusses other causes of differences between theoretical and actual hog.

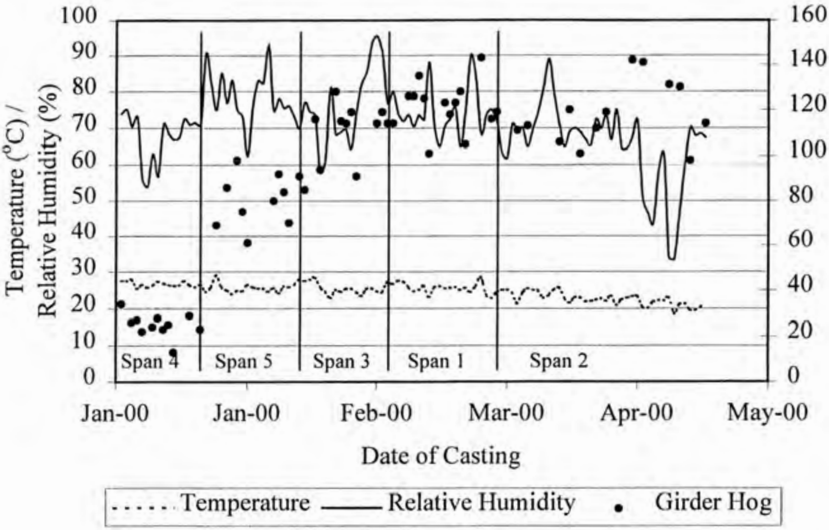

Figure 3: Comparison of Girder Hog with Temperature and Humidity

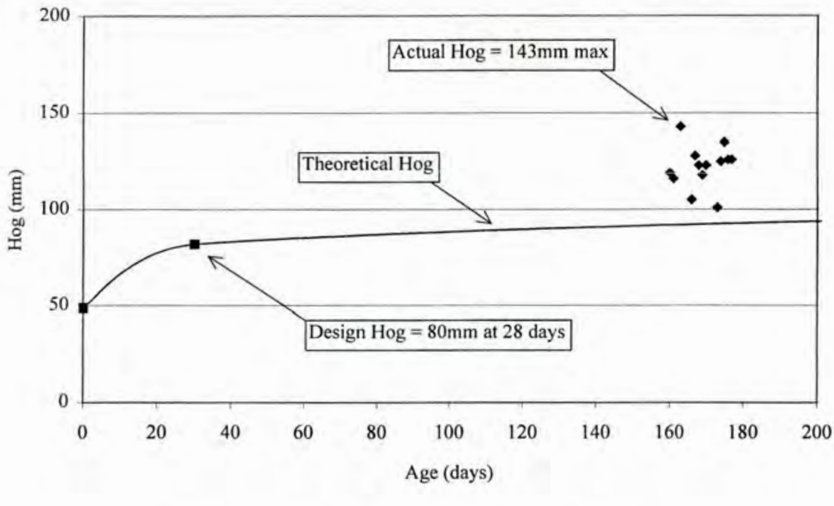

Figure 4: Comparison of Theoretical and Observed Hog

4 DISCUSSION

Girder hog is regarded as being "excessive" either when it exceeds the value predicted by the designer or when it is greater than that exhibited by other girders manufactured to the same design. With respect to the first view, there is a current perception in the bridge construction industry that designers consistently underestimate hog. This suggests that there may be a shortcoming in the theoretical methods being used or in their application by designers. The alternative view is that the discrepancy between actual hog and theoretical hog is related to the manufacturing process. This appears to be supported by the data presented in Figure 3 which indicates that girders which remained in the mould longer (those cast on Friday or Saturday) exhibit the least hog and agree most closely with the theoretical predictions.

Natural variability of hog is a result of the manufacturing process and other sources at the time of erection. This occurs despite Quality Assurance procedures used in the precast industry to achieve consistency of materials and conformity in application of prestress. Girder hog can also vary during the course of a day in response to changes in temperature. Adequate tolerances for these variations should be allowed for in the bridge design.

Hog may be determined by survey or other means by measuring the difference in level at midspan and the ends of the girder. The soffit of the girder is the most reliable datum for comparison of theoretical and actual hog because it is not subject to differences in level due to variations in concrete pour. In practice, however, survey is usually carried out on the tops of the girders as this provides the best data for setting out deck slab levels.

4.1 Parameters affecting Girder Hog

Girder hog is a complex phenomenon which is affected by a number of variables and a small difference in one variable may cause a significant difference in hog. This section concentrates on the individual parameters which contribute to hog. The effect of each component on the overall hog is the subject of the following section.

One of the most significant factors affecting girder hog is the early curing before release of prestress. For most projects a 24 hour casting cycle is adopted using high early strength cement to achieve the required concrete strength at transfer. A typical work day might involve the following: removing the girder cast the previous day from the mould; preparing the mould for the next girder; setting out strands and reinforcement; jacking prestress strands to nominated lock off force; pouring concrete; and steam curing if required. The girder is normally left in the mould overnight and removed the following day. However, most precast facilities operate on a five or six day working week which means that girders cast on a Friday or Saturday are often left in the mould over the weekend and removed first thing on the following Monday. This can significantly reduce girder hog as mentioned previously.

In order to highlight some of the parameters which affect hog, consider the following simple expression for deflection at midspan:

$$\Delta = \frac{5wL^4}{384EI} - \frac{PeL^2}{8EI} \qquad (1)$$

This formula ignores shrinkage and creep effects and is therefore applicable at transfer only. It also assumes the prestressing force and eccentricity are constant along the length of the girder by neglecting the effect of any debonded or draped strands. Nevertheless this expression can provide some insight into potential sources of variability of girder hog.

The self weight, *w*, of a girder is commonly based on a uniform density of $26kN/m^3$ for prestressed concrete. In practice there are local variations in concrete density and steel content (both strands and conventional reinforcement). Some members also have local concentrations of mass due to the presence of diaphragms and solid end blocks. Dimensional tolerances during manufacture can also affect the weight of a girder (Brameld, et al. ,1986).

Errors in girder length, *L*, are unlikely to significantly affect the calculation of hog.

The prestressing force, *P*, reduces over time as losses occur from various effects including concrete shrinkage and creep and steel relaxation. Estimates of prestress losses are unreliable and are one of the primary causes of discrepancy between actual and theoretical girder hog according to Yazdani & Mtenga (1997).

The eccentricity of the prestressing force, *e*, is generally fixed by the strand layout. However, if the force in each strand is not identical then the eccentricity of prestress force and centroid of prestressing strands may not be coincident. Dimensional tolerances of flange thickness, strand setout, etc. may also affect the eccentricity of prestress.

According to the Australian Bridge Design Code, the Modulus of Elasticity of concrete, *E*, may be determined by testing or, as is more commonly the case, by using an empirical expression in terms of the density and mean compressive strength of the concrete at the relevant age. A potential variation of +/-20% in the modulus should be allowed for in design. High early strength cements are often used to minimise production cycle times and can result in much higher concrete strengths than anticipated by the designer. This extra strength is likely to result in greater bending stiffness and reduced hog. In practice, however, this effect appears to be negated by other factors because actual hog is almost always greater than predictions based on theory. One possible explanation for this is the reduced duration of quality curing required to achieve the nominated transfer strength.

Dimensional tolerances not only affect the cross sectional area, but also the second moment of inertia, *I*. An excess of concrete will result in greater mass and greater bending stiffness both of which will reduce hog. Conversely, too little concrete will increase girder hog. The presence of cracks will also significantly reduce the section stiffness. Such cracks may form as the result of excessive girder hog or from handling in the casting yard and vibrations during transportation to site (Yazdani & Mtenga, 1997).

4.2 Errors and their Accumulation

Theoretical predictions of hog should not be regarded as accurate as they contain assumptions and errors which are inherent when modelling any physical process. Traditionally, hog has been estimated using deterministic methods such as those described in Section 2. A sensitivity analysis should always be carried out when using these methods to establish the reliability of the hog estimate. However, to fully appreciate the contribution of individual parameters, a stochastic approach is required in which each component is treated as a random variable with a normal distribution represented by a mean and standard deviation. A statistical analysis can then be performed using a suitable expression for girder hog which includes creep and other effects. This would produce a normal distribution for the resulting girder hog which gives an indication of the range of hog values which could be expected based on the variability of individual parameters. However, apart from being an interesting academic exercise, such an approach is likely to be of little benefit because of the natural variability of hog and number of variables involved.

The results of a sensitivity analysis for girders in Span 1 of the Binstead Way Overpass Bridge are presented in Figure 5. The hog at transfer varies from 35mm to 70mm; the hog at 28 days varies from 58mm to 119mm and the hog after one year varies from 72mm to 148mm. It is interesting to note that most of the measured hog values lie within the error bounds of the sensitivity analysis, albeit consistently above the mean. The sensitivity analysis is based on percentage errors for individual parameters as summarised in Table 2. Although not obtained by experiment, these values are considered representative.

Parameter	Error (%)
W	5
L	1
P	5
E	5
E	20
I	5

Table 2: Percentage Errors for Individual Parameters

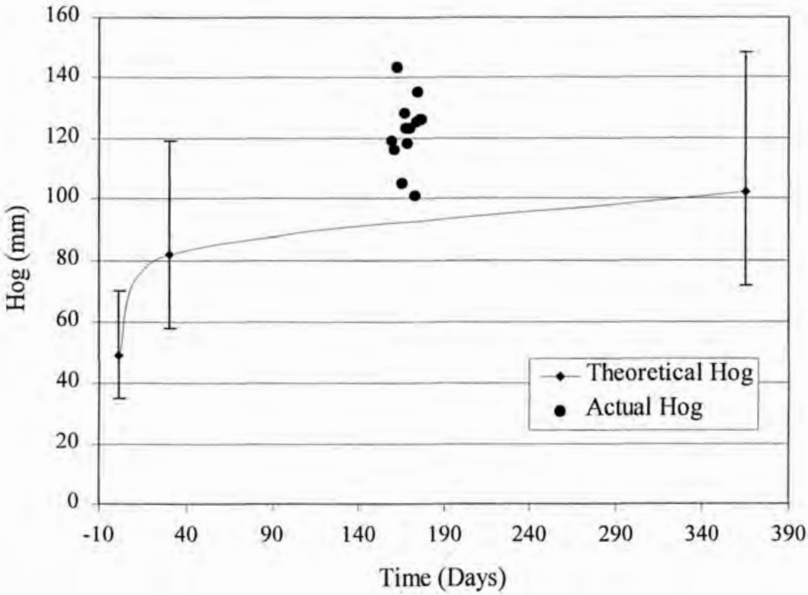

Figure 5: Error Bounds for Theoretical Estimates of Girder Hog

Uncertainty or error in the measurement of any of the individual parameters described above will have some affect on the accuracy of the resulting girder hog. However, of potentially far greater significance is the accumulation of error that occurs as a result of hog being the difference between two numbers of similar magnitude. This is best illustrated by example as shown in Table 3.

Component	*Average Hog (mm)*	*Hog Variation (mm)*	*Percentage Error (%)*
Deflection due to self weight (down)	50	+/- 5	10
Deflection due to prestress (up)	-100	+/- 10	10
Resulting hog (up)	**-50**	**+/- 15**	**30**

Table 3: Accumulation of Error

Assuming percentage errors of 10% for both self weight and prestress deflections, the percentage error of the resulting hog increases to 30%. When the self weight and prestress components are closer in magnitude, the resulting hog value is smaller and the percentage error is greater.

5 RECOMMENDATIONS

In order to reduce the occurrence of problems arising from excessive hog of bridge girders the following recommendations are proposed:

- For long spans where significant variation in hog may be experienced consider setting pedestal levels 50mm higher than would be the case if based on theoretical hog calculations. In this way the pedestal levels can be lowered (or raised) easily if required to account for actual girder hog.

- An equivalent tolerance for girder end rotation should also be considered when selecting bearings. This is in addition to the construction tolerance of 0.0035 radians required by the Australian Bridge Design Code.

- Estimates of hog should be tabulated on bridge drawings for various ages, for example, at transfer, 30 days and 1 year. Design assumptions regarding the age of girders at the time of erection should also be noted on the drawings. Although this is normally 28 days there may be instances where different assumptions have been made.

- Nominating the estimated hog at transfer on the drawings provides the precaster with the opportunity to alert the designer or superintendent if the actual hog is significantly different from that shown on the drawings. Presenting hog values at 30 days and 1 year enables the builder to make adjustments to allow for the actual age of the girders at the time of erection if different from that assumed during the design.

- The deflection of girders under the weight of deck slab should be specified on the drawings. This allows the builder to set edge forms and fix depth markers at regular intervals throughout the slab to which concrete is subsequently poured.

- Where significant additional deflection is expected from construction of parapets, medians, footpaths, and laying of deck wearing surface, the deflection of the composite deck under this weight should also be specified on the drawings.

6 CONCLUSIONS

In general, while the phenomenon of girder hog is well understood, the reasons for its variability are not. Unless allowance for this variation is made during the design of a bridge, problems may arise during construction. This can have substantial cost implications and often leads to antagonism between bridge designers, builders and precasters.

Designers can mitigate the need for costly remedial action by being aware of the limits in the theoretical prediction of girder hog and by making suitable allowance for its variability at the design stage. Builders and precasters should take note of the hog values nominated on the drawings and inform the designer when they vary significantly from the actual girder hog. In this way, adjustments can be made to pedestal levels without undertaking a costly regrade of the bridge deck and approaches.

The subject of girder hog, in particular the issues of variability and growth of hog due to creep, are the subject of a collaborative research project involving Queensland University of Technology, Enco Precast and Connell Wagner.

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