Numerical analysis of bridge falsework Cuplok systems
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Abstract: Bridge falsework systems are frequently used during the construction of cast in place concrete bridges. These structures have a significant impact on the cost, construction rate and safety of the supported permanent structures. However, in recent years a high number of accidents involving bridge falsework systems occurred worldwide. This paper concerns experimental tests of joints of falsework Cuplok® systems. In this paper, the results of 192 tests carried out during the experimental programme will be presented, consisting of five different experiments on three different types of joints. Relevant new results were obtained concerning the bending behaviour and resistance of spigot joints (used to connect two vertical elements) and of forkhead joints (used to connect the falsework system to the formwork system) from which no published research was found to date. Based on the results, joint models are evaluated and improved empirical analytical models are developed. Finally, probabilistic models for the most relevant variables controlling the behaviour and resistance of the cuplok joints (used to connect horizontal elements to vertical elements) will be presented that can be used in the stochastic analysis of falsework Cuplok® systems.

Keywords: temporary works, steel structures, strength & testing of materials.

Experimental analysis of bridge falsework Cuplok systems

1. Introduction

This paper concerns the experimental investigation of joints of bridge falsework structures using the Cuplok® system. Figure 1 illustrates an example of bridge falsework Cuplok® systems. Although this work is included in a project about bridge falsework, the results presented herein are of general application to any falsework system that uses the Cuplok® system, such as shoring, scaffolding and falsework systems used as temporary stages and grandstands.

Bridge falsework are still one of the most commonly used systems during the construction of concrete bridges. They play a significant role in the safety and profitability of a bridge project. Notwithstanding, it was found that construction phase is one of the most critical phases of a bridge life cycle. André et al. (2012), Ratay (2009) and Scheer (2010) provide many illustrative and recent examples of bridge falsework collapses throughout the world. In particular, 73 accidents were found by André et al. (2012) since 1970 in 19 countries. Therefore, there is a need to understand better the structural performance of these structures.

The justification for performing this experimental investigation resides in the important influence of joint behaviour on the overall performance of bridge falsework structures, see André (2014), but also in the large computer resources needed for characterising numerically the joint behaviour, with accuracy and within affordable runtimes, and in the complexity and uncertainty associated with numerical modelling (Pieńko and Błazik-Borowa, 2013).

A experimental programme was developed which included tests of three different joints, see Figure 2: (i) beam-to-column joints (*aka* ledger-to-standard joints or simply cuplok joints), (ii) column-to-column joints (*aka* spigot joints) and (iii) joints at the falsework-formwork interface (*aka* forkhead joints), *i.e.* between forkhead plates and the formwork beams. The objective of the first set of tests is to clarify the differences between published results, see André (2014), and to increase the available database of results to improve existing probabilistic models of certain critical joint structural parameters. The other two types of tests have never been done before (no bibliographic reference was found to date of writing this paper) and thus represent an excellent opportunity to reduce the uncertainties related to the behaviour of falsework structures.

The experimental programme profited from the collaboration with HARSCO Infrastructure, now part of BE&IS (http://www.beis.com/), which supplied tests specimens and provided materials' related information. The steel grade of the materials used in the experimental tests is grade 50 according to BS 4360 (BSI, 1990), with a nominal yield stress of 355 MPa (355 N/mm^2).

Unfortunately, tensile tests of steel coupons taken from each different element used in the tests could not be performed due to time constraints related to the use of the available testing facilities. However, information was made available by HARSCO, see Table 1, regarding the mechanical properties of the steel of various elements, namely ledgers and standards, given in the factory production control certificates of the batches of each of the elements used in this study. These certificates are based on a sample size of tensile tests results far larger than the one that could be considered from the elements used in the present study and therefore provide an accurate estimate of the tensile mechanical properties of the population of each of the elements. Since the elements tested are a representative sample of the population, the values shown in Table 1 constitute a reference that must be adequately considered when applying the results presented in this paper, namely the values of the parameters of the suggested joint models, in the design of falsework systems.

Geometrical characteristics of the various elements of the Cuplok® system were measured and the complete results are presented in André (2014). The results of the geometrical measurements made from standard and ledger elements are presented in Tables 2-3, respectively.

The results obtained with this experimental study have been later incorporated in advanced numerical models of bridge falsework Cuplok® systems, resulting in very accurate and precise numerical results (André et al., 2014), improving upon results of previous numerical studies. These numerical models were then used to assess the structural robustness, structural fragility and structural risk of bridge falsework Cuplok® systems (André et al., 2015, 2017), contributing to understand and decrease the existing risks associated with their operation.

2. Past experimental research of bridge falsework

Experimental investigations are an essential tool for any pioneer research. Nowadays they provide the benchmarks for validating the results of numerical models, but not so far ago experimental tests were the only available method to develop design rules for structural systems.

Past experimental investigations on bridge falsework systems consist predominantly on joint testing, although some full-scale tests of representative parts of structural systems have also been performed, see André (2014) and Beale (2014).

Early in the 1990s, Voelkel (1990) carried out an experimental assessment of Cuplok® systems developed by SGB (now part of BE&IS). Several types of tests were performed to determine the values of looseness, stiffness and resistance of ledger-to-standard (cuplok) joints. In particular, ten cyclic tests were performed (where the load was applied in cycles of increasing amplitude) to derive the maximum bending stiffness of the joint about the joint strong bending axis (see Figure 3). The tests results showed that looseness in the joints affects the initial bending stiffness of the connection which is much lower than the one determined after the ledger element locks-in at the cuplok joint. In UK, Godley and Beale (1997) carried out similar tests obtaining very comparable results.

Recently, results from a research carried out at the University of Sydney have been published concerning cuplok joint bending tests (Chandrangsu and Rasmussen, 2011a) and full-scale tests (Chandrangsu and Rasmussen, 2011b). For the former tests, the adopted test setup and method was similar to the ones already mentioned, but applying the load monotonically straight up to joint failure.

A summary of the results obtained in the abovementioned studies is given in Table 4. Comparing the results, the major differences between the studies are the results obtained for the bending stiffnesses about the cuplok joint strong axis, in particular regarding the existence and influence of joint looseness.

Experimental studies of other types of joints have been published by Abdel-Jaber et al. (2009), Liu et al. (2010) and Peng et al. (2013, 2015).

The present paper builds up upon the data presented in André et al. (2011, 2013) but significantly expands the information provided concerning the scope, details and discussion of the results obtained during the experimental investigation.

3. Ledger-to-standard (cuplok) joint tests

As the results of past cuplok bending tests are not consistent, a series of cantilever bending tests was performed in the present study. It was also investigated the possible influence in joint behaviour of using “as new” and “used” elements. To this end, half of the tests were performed with used elements whilst the other half with “as new” elements. However, the “used” materials delivered by HARSCO were, in general, in excellent conditions with only minor damage observed in just a few elements. The latter had a relevant impact on the results obtained.

In addition to bending tests, tensile tests were also performed to characterise the behaviour and resistance of ledger-to-standard joints under axial loads.

3.1 Joint bending tests

Bending tests were performed in two orthogonal directions: (i) about the joint strong axis (rotations caused by displacements along local y axis) and (ii) about the joint weak axis (rotations caused by displacements along local z axis). The strong and weak axes are illustrated in Figure 3. For each direction, tests were carried out with two, three or four ledgers connected at the cuplok joint to analyse the influence in the joint's behaviour of the number of elements connected, see Figure 4.

The test setup consisted of a 500 mm standard element clamped at the upper and lower ends to a rigid frame by bolted connections. The cuplok joint was positioned at the centre of the standard and a 600 mm ledger (termed hereafter as the loaded ledger) plus one to three shorter ledger elements, with 50 mm length, were connected at the joint (depending on the tested joint configuration: with two, three or four ledger elements, respectively).

Loading was introduced by applying a vertical displacement at the loaded ledger element using a hydraulic jack. A constant low displacement rate equal to 0.1 mm/s was used. The resulting load was measured by a load cell positioned at the top of the jack.

3.1.1 Strong axis bending tests

The test procedure consisted in applying a vertical displacement at the loaded ledger element using a lever arm equal to 300 mm, see Figure 5. During the tests, the load (registered by a load cell), the jack displacement (registered by LVDT 01) and the joint rotation (calculated through LVDTs N1 and N2 readings) were measured and recorded every second.

Two sets of tests were performed, with different test methods: (i) a set of initial tests and (ii) a set of final tests.

The objective of the initial tests was to assess if the results obtained by past investigations, in particular (Chandrangsu and Rasmussen, 2011a), could be reproduced. Therefore, in this set, loading was applied monotonically up to complete joint failure. The tests confirmed the results reproducibility which allowed comparing the existing test results with the ones obtained in this study.

In the set of final tests, loading consisted in applying at the start of each test, three consecutive cycles of ±2 mm amplitude, followed by an additional three consecutive cycles of ±3 mm amplitude. This test method was devised to simulate the behaviour of the joints under cyclic loads, e.g. introduced by wind action. Next, the test method continued with the monotonic application of displacements upwards, or downwards, until the point where the load *vs*. displacements curve began to deviate from linearity (which occurred around 2/3 of the maximum bending resistance of the joint). Once the latter point was reached, the joint was gradually unloaded, after which loading was reapplied monotonically in the opposite orientation (named hereafter as the reloading phase) until the joint failed (see Figure 6). This test method tried to simulate a possible inversion of flexural load transfer, i.e. from hogging to sagging bending moment at the joint. Note that the results obtained with this type of test procedure have not been published before.

In the set of final tests, the effect of locking the joint by hand rather than by hammer was also studied, as well as the effect of increasing ten times the loading rate after the application of the initial cycles, from 0.1 mm/s to 1 mm/s in order to simulate the dynamic effect of a potential sudden failure event occurring within the bridge falsework system.

A total of 96 tests were carried out: 36 initial tests and 60 final tests. Figure 7 illustrates the results obtained for upward and downward rotations when correctly locking the joint under a low loading rate. Figure 8 illustrates the results obtained for the two distinct cases of locking the joint by hand and by hammer, under a low loading rate. Figure 9 illustrates the results obtained for the two distinct cases of applying a low loading rate and a high loading rate.

The bending moment *vs*. joint rotation (M *vs*. θ) curves, in each loading quadrant, were fitted by a multilinear regression model with three linear segments (tests without looseness, with slopes k_2 to k_4) or four linear segments (tests showing looseness, with slopes k_1 to k_4), see Figure 10.

In Tables 5-6, the results of the loading stiffness (k_1 to k_4), rotation increments ($\Delta\theta_1$ to $\Delta\theta_4$), unloading stiffness (k_U) and ultimate bending moment resistance (M_u) are given for each of the joint configurations tested. The unloading stiffness (k_U) was determined using the values of the unloading curve within the 90% and 10% range of the ultimate bending moment resistance. Note that these parameter values characterise the joint behaviour under a low loading rate (e.g. 0.1 mm/s) and adequate joint clamping (e.g. by hammer blows). The corresponding parameter values for the reloading phase, for a high loading rate (i.e. 1 mm/s) and for inadequate joint clamping (i.e. by hand) are provided in André (2014).

In order to be able to fully interpret the results obtained in the various types of tests performed in this study and in order to be able to compare the results obtained for different groups of tests, statistical analyses of the results were performed. In addition, to aid the interpretation of the results, box plots were developed for each set of results. The complete analysis is given in André (2014).

From the analysis of the tests results, several important observations could be made:

- Looseness can be asymmetrically distributed in the joint. From all tests results, the average value of initial looseness of the cuplok joint bended about its strong axis is equal to 0.0075 rad (≈0.43º);
- By averaging all tests results, the effect of the initial cycles may not be perceptible (Savage, 2009). However, for each particular test, the application of the initial cycles could lead to an important increase in the looseness and to a significant decrease of the initial stiffness; or vice-versa. For example, it was observed that after the last initial cycle, looseness can increase by 0.006 rad or decrease by 0.009 rad when compared with the value at the first initial cycle, whilst the stiffness can more than double or can decrease to just a fraction of the initial value. This effect is important to both the serviceability and ultimate limit states range and justifies the need for carrying out cyclic tests (André 2014). Therefore, testing monotonically to failure could lead to artificially high initial stiffness values;
- No statistical basis was found to support considering the cuplok joint behaving differently for upward and downward rotations (see Figure 7). The same conclusion could be made for the results obtained with "as new" and used elements, which derives greatly from the fact, already mentioned, that the used elements sent by HARSCO were all in excellent conditions;
- It was found that tightening the joint by hand doubles, on average, the joint looseness values. By performing a *t-test* hypothesis testing analysis, using a *p-value* equal to 5%, it was also possible to verify that the mean value of the k_2 stiffness for tests locked with a hammer and by hand may not belong to the same population. It was also possible to determine that locking the joint by hand led to an average reduction of about 30% in the k_2 stiffness value (see Figure 8);
- It was also possible to observe that cuplok joints could not endure more than two complete hysteretic cycles in the plastic range, and that there is a degradation of the joint monotonic stiffness and resistance with cyclic loading and increased loading rate (see Figure 9);
- It could be statistically demonstrated that the joint stiffness after looseness (i.e. k_2 in Figure 10) is lower (about 20% less) in the reloading segments when compared to the k_2 stiffness in the loading segments, see Figure 7 and André (2014);
- Comparing the joint models adopted in the present work and by past studies, namely the recent Australian study (Chandrangsu and Rasmussen 2011a), see Figure 11, it is possible to observe that the model adopted in this work provides an improved fit to the overall tests results with little added complexity.

3.1.2 Weak axis bending tests

The test setup adopted for the weak axis bending tests was essentially the same as described for the bending tests about the strong axis, apart from a 90º rotation of the standard element about the loaded ledger axial axis. In all 48 tests, the joint was locked by applying downward hammer blows to the cup.

Only one ledger was positioned at the cuplok joint. For this limit case configuration, the joint stiffness, in the weak axis, comes mainly from the friction between surfaces of the ledgers in contact with surfaces of the standard and of the cups. No other significant form of restraint is mobilised. Thus, the joint stiffness strongly depends on the effectiveness of the joint locking method.

For upward rotations, the only restraint left after the force value becomes larger than the restraint provided by static friction coefficient, comes from the kinetic friction coefficient resulting in a very low joint stiffness value. For downward rotations, the joint stiffness also diminishes but still to a value higher than the one for upward rotations. This occurs because for downward rotations the joint rotation coincided with the torsion rotation applied to the cup to lock the joint, so the additional contact pressure generated provides some stiffness to the joint.

For these test conditions no real failure of the joint was attained. All tests were stopped when a large joint rotation value was attained or when the load value registered from the jack load cell consistently dropped.

Comparing the results with the ones obtained for the bending tests about the strong axis, it was possible to conclude that the joint in the weak direction is several times less stiff. In particular, joint stiffness was found to be negligible if the joint was locked by hand. This finding highlights again the importance of a correct locking of the joints.

3.2 Joint tensile tests

As there is only limited information (ten results showing a large variability, see Voelkel (1990)) about the tensile strength of cuplok joints and no information is available regarding its stiffness, 12 tensile tests of cuplok joints were performed.

The test setup adopted is illustrated in Figure 12. Two ledgers were connected to a cuplok joint at diametrically opposed positions and the end extremities clamped to the test machine grips.

The load was introduced by moving the lower grip downwards, monotonically at a rate of 0.2 mm/min, producing tension strains in the ledgers, until complete joint failure (see Figure 13).

Analysing the results, see Figure 14, it is possible to observe that joint looseness was present in half the tests. In addition, the results using “as new” elements (dashed curves) and used elements (solid curves) are similar. However, the tests using “as new” elements exhibited a smaller deformation capacity than the tests with used elements. This finding highlights the importance of proper manufacturing of the joint components to avoid structural defects.

It was also found that increasing the number of ledgers at the joint leads to an increase of the maximum tensile resistance of the joint (P_u), but no statistical support was found between this variable and the joint tensile stiffness. Tables 7-8 contain the results of the joint parameters that best fit the multilinear model presented in Figure 10.

4. Spigot joint tests

Various types of spigot joints can be used in falsework structures: (i) the spigot can be shop welded to the lower standard internal wall or (ii) it can be an independent element. The external dimensions of the spigot (usually an SHS or CHS element) are smaller than the internal diameter of the standards’ CHS. Therefore, an initial play exists which might lead to initial member and global geometrical imperfections.

As the full-scale tests carried out in Australia (Chandrangsu and Rasmussen 2011b) demonstrated, the maximum resistance of bridge falsework systems is often limited by the strength of the spigot joints. Enright et al. (2000) developed a mechanical model to account for the spigot joints in the design of falsework structures, but no validation of this model was provided.

In the present study, a series of spigot joint bending tests, with or without compressive load, were performed in order to assess the behaviour and resistance of this type of joint. The test setups for each type of test (with and without compressive load) are illustrated in Figures 15-16.

The welded spigot was selected as it is the most commonly used type of spigot joint. The spigots had a SHS with 32 mm nominal side length, 3.2 mm nominal wall thickness and 150 mm nominal free length measured from the top section of the lower standard, for a total length of 300 mm. The material grade was steel grade 50 according to BS 4360 (BSI, 1990) with a nominal yield stress of 355 MPa.

Note that the test method given in the European standard BS EN 15512 (BSI 2009) does not always return conservative values of the resistance and bending stiffness of the spigot joint. In fact, as the spigot joint involves a contact problem, the most conservative test method can correspond to the application of a high lateral load to axial load ratio. High values of the latter ratio result in contact areas between the upper and lower standards, in principle, smaller than the ones obtained for lower load ratios. As the joint stiffness varies proportionally with the bearing contact area, high load ratios imply lower values of the resistance and bending stiffness of the spigot joint (André, 2014).

In order to make a good decision regarding the load ratios to be used, a limited number of initial tests were carried out. In the final tests, the load ratios chosen were equal to 20% and 50%; some additional tests were carried out without axial load (i.e. only a lateral load was applied).

A total of 27 tests were performed, 6 initial tests and 21 final tests. The lateral load and the axial load (when applicable) were applied at a low displacement rate (0.01 mm/s) until complete joint failure (see Figure 17). The lateral load was applied at the interface between the two standard elements (i.e. at the centre of the spigot). In all tests where a compressive load was applied, the latter was applied first. The loads were applied throughout tests in steps of not more than 5 kN.

The results of the final tests are presented in Figs. 18-20. The test label includes the lateral load to axial load ratio (e.g. TA20 represents a test where the ratio was equal to 20%) and the condition of the elements: new (N) and used (U). For the tests using a load ratio equal to 20%, failure could not be attained because the applied axial load reached values close to the maximum pressure limit of the pump used. Also note that the initial behaviour of the joints is not represented because it was difficult to coordinate the initial application of the lateral and axial loads.

It is possible to observe that the results obtained with used elements are, in general, less stiff and less resistant than the ones obtained using “as new” elements. This observation is justified by the presence of structural defects at the welds between the spigot and the inner wall of the standard. This finding highlights the importance of proper material maintenance and site inspection procedures.

The spigot joint behaviour can be simulated using the model already used for the bending tests about the strong axis of cuplok joints, see Figure 10. Tables 9-10 contain the results of the model parameters.

With the results obtained it is also possible to assess if the mechanical model proposed by Enright et al. (2000) is valid. Nonlinear numerical models were developed to simulate the spigot tests using the mechanical model proposed by Enright et al. (2000). The material of the spigot was considered the same as of the standards, with a Young’s modulus equal to 210 GPa, a yield stress of 400 MPa and a tensile resistance of 500 MPa (for a strain equal to 20%). Analysing the results given in Figure 21, it can be observed that the effect of the axial load on the stiffness and resistance of the spigot joint cannot be well captured by the mechanical model proposed by Enright et al. (2000), returning unsafe values of the bending resistance for low lateral load to axial load ratios and overestimating the bending stiffness for high ratios.

Therefore, it is suggested to replace the existing mechanical model by the phenomenological structural model presented in this study.

5. Forkhead joint tests

The joint between the top of the falsework system and the formwork system is in general a grey area. The stiffness and resistance of the joints between the falsework and the formwork depends on the type of the falsework top element (forkhead or baseplate) and on the geometrical, material and stiffness characteristics of the formwork beams and formwork system as a whole.

Despite the large uncertainties associated with this joint, it is important to perform a structural assessment which can be valid for cases where general good practices are followed during planning, design and operation. Therefore, ten bending tests of the joint materialised by the interaction between the forkhead plate and the formwork beam were carried out, five over each one of the two bending axes of the forkhead plate (see Figure 22(a)). The nominal dimensions of the forkheads were 106×150×162×8 mm (Height × Length × Width × Thickness), see Figure 22(b). The formwork beam was simulated by a 300×130×500 mm (Length × Width × Height) timber (pine) block.

By virtue of the dimensions of both the timber block and of the forkhead there was a gap close to 10 mm between the inner side of the forkhead side plates and the timber block. No additional elements were used to close it. The gap was made equally distributed in both sides of the timber block before each bending test about axis 1. In the bending tests about axis 2 (see Figure 23), the gap was unequally distributed to a single side so as to test the joint in the most unfavourable configuration. The value of this load eccentricity, equal to 20 mm, corresponds to the average value obtained in the construction sites survey published in Chandrangsu and Rasmussen (2011a).

The forkhead rotation was determined in the same way as the rotation of each standard element in the spigot joint tests. The lateral displacements were measured at the tube segment of the forkhead element, see Figure 22(b). Provided that the tube segment does not deform, i.e. behaves like a rigid segment, the rotation (θ) calculated based on the measured displacements corresponds to the joint rotation at the forkhead, see Figure 24(a). However, because the tube segment is not a rigid element it will deform, thus the corresponding joint rotation overestimates the true value of the forkhead rotation (nevertheless an error on the safe side).

In order to estimate if the tube segment deformed plastically (thus contributing significantly to the calculated joint rotation value), the length of the tube was measured before and after each forkhead joint test. In addition, measurements were also made of the distance between forkhead side plates, before and after each test.

The loading method was the same as for the spigot joint tests. However, only one lateral load to axial load ratio was chosen: 50%.

For bending tests about axis 1, the joint rotation occurred only due to deformations at the tube segment and no rotation of the forkhead was observed. Therefore, the forkhead rotational stiffness about axis 1 can be considered as rigid. In this axis, failure was attained by buckling of the most stressed hole region located at the tube segment.

For bending tests about axis 2, the rotation occurred mainly at the forkhead while the tube segment deformed elastically (confirmed by the measurements made before and after each test). For this axis, the forkhead suffered plastic deformations resulting in an increase of the distance between side plates in the range of 2 to 7 mm. In this axis, all tests were stopped when the rotation of the element was clearly visible, see Figure 24(b). Therefore, the maximum resistance of the forkhead element was not determined. The tests results for bending axis 2 are illustrated in Figure 25.

As for the other types of tests, the M vs. θ curves can be analysed using the model presented in Figure 10. Tables 11-12 contain the results of the joint parameters for bending about axis 2.

The tests results show that it is possible to mobilise an important bending stiffness at the interface between the falsework and the formwork if it is correctly designed and assembled, and these conditions remain throughout their use.

It must be again stressed that the bending stiffness at the interface between the falsework and the formwork also depends on the characteristics of the formwork system, including the stiffness and geometrical dimensions of the formwork beams. In the tests carried out, the width of the timber block selected to represent the formwork beam was equal to 130 mm which is relatively large compared with the most common values, typically smaller than 80 mm. Larger width beams mean larger contact surfaces which can result in higher bending stiffness than when a smaller width beam is used. This difference may be reduced considerably if wedge elements are used to bind the formwork beam to the forkhead side plates, as good construction practices recommend but are not always followed.

6. Probabilistic models for cuplok joints

In the following, the methodology used for selecting the appropriate model for the most important variables that characterise the cuplok joint behaviour under bending loads over the strong axis is presented; for other joints, see André (2014). These variables are the initial looseness ($\Delta\theta_1$), the k_1 and k_2 stiffnesses, the rotation associated with the last linear segment ($\Delta\theta_4$) and the ultimate bending moment resistance (M_u). Only the results obtained in tests where the joint was locked by a hammer and loaded with a slow displacement rate were used.

The probability distributions considered in the analysis were: the Normal distribution, the Log-normal distribution, the Gamma distribution, the Logistic distribution, the Weibull distribution and the Gumbel distribution. Additionally, truncated versions of these distributions were also considered, see Table 13. The *R* program (R Core Team, 2012) was used to perform the various analyses. The parameters of the distributions were determined by the Maximum Likelihood method using the *R* package *fitdistrplus* (Delignette-Muller et al., 2012).

First, for a graphical analysis, the different distributions *pdf*s were plotted against the data histogram and the same for the distributions *cdf*s against empirical *cdf*. Q-Q plots for selected distributions were also studied (Q-Q plots were preferred to P-P plots because they allow a better visual analysis of the tails of the distribution). Next, classical hypothesis testing methods, considering a statistical significance value equal to 0.05 and a null hypothesis of accepting the distribution were performed. Both Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) statistics were determined. In addition to the classical goodness of fit tests, other types of analysis were also carried out: the Log-Likelihood (loglike) and the Akaike information criterion (AIC). The distribution with the highest loglike and lowest AIC values corresponds to the model that best fits to the input data.

The decision concerning selecting a probabilistic model must primarily consider the mechanical behaviour of the components being studied. In the end, the probabilistic models were selected based on conservative criteria. For example, it is more conservative to analyse bridge falsework systems having larger joint looseness, so models that have a better fit in the range of high values of looseness were preferred. The selected truncated distributions are presented in Table 14. The values of the distributions' parameters are given in Table 15. The results show that in some parameters the most suited distributions deviate greatly from normality, which was assumed by Zhang et al. (2010, 2011).

The Spearman (rank-order) correlation coefficients (matrix) between looseness ($\Delta\theta_1$), k_1 and k_2 stiffness, the k_4 rotation increment ($\Delta\theta_4$) and the ultimate bending moment resistance (M_u) were obtained. Significance tests were also performed in order to distinguish between a spurious correlation present in the sample and a correlation with statistical support that can be expanded to the population, see André (2014). It could be concluded that it is likely that the values of k_2 stiffness for the load and reload segments are positively correlated. The same conclusion could be drawn for the values of M_u with the values of k_2 for the load and reload segments; and for the values of $\Delta\theta_4$ and M_u (André, 2014).

7. Conclusions

Bridge falsework systems, in particular those constituted by proprietary modular framed systems of steel elements connected by special couplers, such as the Cuplok® system, are frequently used during the construction of cast in situ concrete bridges. A total of 192 joint tests were carried out divided in bending and tensile tests of joints connecting vertical elements (standards) to horizontal elements (ledgers), in bending tests of joints connecting two different adjacent standards and finally in bending tests of joints connecting the top sections of falsework structures to the formwork assembly.

From the first lot of tests it was possible for the first time:

- to demonstrate experimentally the influence of initial rotation cycles with small amplitude on the looseness and initial stiffness (after looseness) of the ledger-to-standard joints. It could be concluded that their effect could be important in both the serviceability and ultimate limit states which justifies the need for carrying out tests with initial cycles;
- to demonstrate experimentally the degradation of the behaviour of these joints with hysteretic cycles. It could be concluded that the joint stiffness tends to be lower (20% less) in reloading segments when compared to loading segments;
- to demonstrate experimentally the degradation of the behaviour of these joints when they are not correctly locked. It could be concluded that tightening the joint by hand doubles the joint looseness values. This increased looseness contributes to an average 30% decrease in the stiffness of the joint.

From the second lot of tests it was possible for the first time:

- to characterise experimentally the bending stiffness and resistance of spigot joints under three different lateral load to axial load ratios. It could be concluded that the values of the bending stiffness, as well as those of the resistance, diminish with increasing lateral load to axial load ratios, and that imperfections at the spigot welds have a detrimental effect on the spigot joint behaviour and resistance;
- to verify the accuracy of existing spigot mechanical model joints. It could be concluded that the effect of the axial load on the stiffness and resistance of the spigot joint cannot be well captured by the existing mechanical models.

From the third lot of tests it was possible for the first time:

- to characterise experimentally the bending stiffness and resistance of a possible solution of forkhead joints under axial load and bending moment. It could be concluded that it is possible to mobilise an important bending stiffness at the interface between the falsework and the formwork if it is correctly designed, assembled and used throughout the operation.

Finally, as an example, the results of the strong axis bending tests for the cuplok joint were analysed statistically. The selection of the probabilistic distribution for each parameter was based on classic goodness of fit tests but also on more advanced analysis. The results show that for some parameters the most suited distributions deviate greatly from normality.

The results and information presented in this paper led to the improvement of the accuracy and precision of advanced numerical models which were used to assess the resistance, structural robustness, structural fragility and structural risk of bridge falsework Cuplok® systems, contributing to understand and decrease the existing risks associated with their operation.

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FIGURES

All Figures are suited to be printed in black and white.

Figure 1 Example of bridge falsework Cuplok® system

Figure 1 shows an example of a bridge falsework Cuplok® system.

(a) Cuplok joint

(b) Spigot joint. Adapted from SGB (2009)

(c) Forkhead joint. Adapted from SGB (2009)

Figure 2 Types of joints of bridge falsework Cuplok® systems

Figure 2(a) shows a 3D view of the cuplok joint.

Figure 2(b) shows a 3D view of the spigot joint.

Figure 2(c) shows a 3D view of the forkhead joint.

NOTE to Editor: Both Figure 2(b) and Figure 2(c) resemble figures presented in the SGB Cuplok manual, but contain changes that allow them to be considered new Figures without any existing copyrights. Acknowledgement is made to SGB Cuplok manual.

Figure 3 Illustration of bending axes of the cuplok joint

Figure 3 shows the bending axes of the cuplok joint.

Figure 4 Illustration of cuplok joint configurations tested (*xz* plan view)

Figure 4 shows the different configurations (in terms of the number of ledgers) tested for the cuplok joint.

(a) Schematic illustration

(b) Overview of test setup

Figure 5 Testing setup of bending tests (strong axis)

Figure 5(a) shows a schematic illustration of test setup.

Figure 5(b) shows an overview of test setup.

(a) Upward loads, “as new” and used elements

(b) Downward loads and “as new” elements

(c) Downward loads and used elements

Figure 6 Modes of failure observed during cuplok bending tests, strong axis

Figure 6(a) shows a detail of a failure by cracking of the weld of the welded cup observed in tests where load (displacement) was applied upwards.

Figure 6(b) shows a detail of a failure by cracking of the wall of the free cup observed in tests where load (displacement) was applied downwards, for new elements.

Figure 6(c) shows a detail of a failure by cracking of the blade of the loaded ledger observed in tests where load (displacement) was applied downwards, for used elements.

Figure 7 Final tests. Strong axis bending test results for cuplok joints with two ledgers for upwards and downwards displacements considering used and as new elements

Figure 7 shows the Bending moment vs. joint rotation curves obtained for the final bending tests of the cuplok joint (strong axis) with two ledgers for upwards and downwards displacements considering used and as new elements.

Figure 8 Final tests. Strong axis bending test results for cuplok joints with two ledgers for hand locked and hammer locked joints considering used and as new elements

Figure 8 shows the Bending moment vs. joint rotation curves obtained for the final bending tests of the cuplok joint (strong axis) with two ledgers for hand locked and hammer locked joints considering used and as new elements.

Figure 9 Final tests. Strong axis bending test results for cuplok joints with two ledgers for low loading rate and high loading rate considering used and as new elements

Figure 9 shows the Bending moment vs. joint rotation curves obtained for the final bending tests of the cuplok joint (strong axis) with two ledgers for low loading rate and high loading rate considering used and as new elements.

Figure 10 Multilinear model used to simulate the *M vs.* θ loading curves of the cuplok joint
Figure 10 shows the multilinear model used to simulate the *M vs.* θ loading curves.

Figure 11 Comparison of the fit of the joint model proposed in the present work and by Chandrangsu and Rasmussen (2011a) to a set of cuplok joint bending test results - two ledgers joint configuration, strong axis bending tests, low loading rate and adequate joint tightening by hammer blows
Figure 11 provides a comparison between the multilinear model presented in this work and on a previous study, and their fit to the curves of all tests performed using two ledgers at the cuplok joint, including some obtained in the previous study.

(a) Schematic illustration (b) Overview of test setup
Figure 12 Setup for the tensile test of the ledger-to-standard joints
Figure 12(a) shows a schematic illustration of test setup.
Figure 12(b) shows an overview of test setup.

(a) Welded cup failure (b) Free cup failure (c) Slippage of the bottom ledger
Figure 13 Modes of failure observed during cuplok joint tensile tests
Figure 13(a) shows a detail of a failure by deformation of the wall of the welded cup observed in the tensile tests.
Figure 13(b) shows a detail of a failure by cracking of the wall of the free cup observed in the tensile tests.
Figure 13(c) shows a detail of a failure by slipping of the blade of the bottom ledger observed in the tensile tests.

Figure 14 Test results of cuplok joint tensile tests considering used and as new elements
Figure 14 presents the axial force vs. joint axial displacement curves for the tensile tests of the cuplok joint considering used and as new elements.

(a) Schematic illustration (b) Overview of test setup
Figure 15 Setup for the combined bending and axial load spigot joint tests
Figure 15(a) shows a schematic illustration of test setup.
Figure 15(b) shows an overview of test setup.

(a) Schematic illustration (b) Overview of test setup
Figure 16 Setup for the simple bending spigot joint tests
Figure 16(a) shows a schematic illustration of test setup.
Figure 16(b) shows an overview of test setup.

(a) Plastic deformations around spigot holes and at the spigot element (b) Cracks in spigot welds (c) Slippage of the spigot element
Figure 17 Modes of failure observed during spigot joint tests
Figure 17(a) shows three details (1 to 3) of a failure by deformation of the spigot element (detail 3) and cracking and ovalisation of the wall of the standard around the hole region (details 1 and 2).
Figure 17(b) shows a detail of a failure by cracking of the weld connecting the spigot element to the internal wall of the standard.
Figure 17(c) shows a detail of a failure by slipping of the spigot element relative to the standard.

Figure 18 Test results of spigot joints for a lateral load to axial load ratio equal to 20%
Figure 18 shows the Bending moment vs. joint rotation curves obtained for the bending tests of the

spigot joint (load ratio equal to 20%).

Figure 19 Test results of spigot joints for a lateral load to axial load ratio equal to 50%
Figure 19 shows the Bending moment vs. joint rotation curves obtained for the bending tests of the spigot joint (load ratio equal to 50%).

Figure 20 Results of spigot joints simple bending tests
Figure 20 shows the Bending moment vs. joint rotation curves obtained for the bending tests of the spigot joint (simple bending tests).

(a) Load ratio equal to 20%
(b) Simple bending
Figure 21 Comparison of the mechanical model suggested in Enright et al. (2000) with the spigot joint bending tests results
Figure 21(a) shows the Bending moment vs. joint rotation curves obtained for the bending tests of the spigot joint (load ratio equal to 20%), together with the curve obtained for the mechanical model suggested in the literature.
Figure 21(b) shows the Bending moment vs. joint rotation curves obtained for the bending tests of the spigot joint (simple bending tests) together with the curve obtained for the mechanical model suggested in the literature.

(a) Forkhead joint bending axes (b) Nominal dimensions of the forkhead
Figure 22 Forkhead element
Figure 22(a) shows the bending axes of the forkhead joint.
Figure 22(b) shows the dimensions of the forkhead element (Forkhead + tube segment).

(a) Schematic illustration (b) Overview of test setup
Figure 23 Setup for the combined bending and axial load forkhead joint tests
Figure 23(a) shows a schematic illustration of test setup.
Figure 23(b) shows an overview of test setup.

(a) Conceptual model for the calculation of forkhead joint rotation (b) Observed rotation
Figure 24 Forkhead joint rotation about axis 2
Figure 24(a) shows the conceptual model used to derive the forkhead joint rotations.
Figure 24(b) shows a view during the test where it is clear the bending of the forkhead.

Figure 25 Test results of forkhead joints for the bending tests about axis 2, load ratio equal to 50%
Figure 25 shows the Bending moment vs. Joint rotation curves for the five bending tests about axis 2 performed for the forkhead joint.

TABLES

Table 1 Steel mechanical properties given in factory production control certificates of the ledgers and standards used in the tests

3400 samples	Yield strength (MPa)	Tensile strength (MPa)	Elongation after fracture (%)
Mean value	449.74	524.22	24.98
Required limits	>355	470-630	>20

Table 2 Geometrical characteristics of the standards used in the tests, CHS sections

56 measurements	Wall thickness (mm)	External diameter (mm)
Average value (mm)	3.5	48.7
Standard deviation value (mm)	0.1	0.2
Nominal value (mm)	3.2	48.3

Table 3 Geometrical characteristics of the ledgers used in the tests, CHS sections

10 measurements	Wall thickness (mm)	External diameter (mm)
Average value (mm)	3.4	48.6
Standard deviation value (mm)	0.2	0.1
Nominal value (mm)	3.2	48.3

Table 4: Summary of the joint test results of Cuplok® systems published in past studies

Reference	Joint type	Type of test	Initial stiffness (average values)	Resistance (average values)	Additional information
Voelkel (Voelkel, 1990)	Ledger-to-standard (cuplok joint)	Cyclic joint bending tests	78 kN.m/rad* (strong axis. after looseness)	2.9 kN.m (strong axis)	Standards, ledgers and braces: 48.3 × 3.2 (mm) CHS, S355 steel
		Cyclic frame tests	5.6 kN.m/rad (weak axis, no looseness)	0.2 kN.m (weak axis)	
		Monotonic joint tensile tests	—	73 kN	
	Brace-to-standard (swivel joint)	Cyclic tensile tests	1360 kN/m	28 kN	
Godley and Beale (1997)	Ledger-to-standard (cuplok joint)	Cyclic joint bending tests	65 kN.m/rad* (strong axis, after looseness)	2.9 kN.m (strong axis)	
Chandrangsu and Rasmussen (2011a)	Ledger-to-standard (cuplok joint)	Monotonic joint bending tests	41 kN.m/rad (strong axis, with looseness) 77 kN.m/rad (strong axis, after looseness)	3.5 kN.m (strong axis)	Standards: 48.3 × 4.0 (mm) CHS, S450 steel Ledgers: 48.3 × 3.2 (mm) CHS, S350 steel

* In tests performed by Voelkel and Beale, the initial stiffness with looseness was determined to be equal to 10% of the stiffness value after looseness.

Table 5 Results of the bending stiffness for the multilinear model of the cuplok joint in loading (strong axis bending tests)

Joint configuration	k_1		k_2		k_3		k_4	
	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV
Two ledgers (2L)	19.30	0.74	70.82	0.14	22.79	0.27	5.38	0.57
Three ledgers (3L)	10.56	0.65	83.44	0.24	12.76	0.44	2.52	0.44
Four ledgers (4L)	16.96	0.86	85.85	0.19	20.91	0.30	3.18	0.42

Table 6 Results of other parameters for the multilinear model of the cuplok joint in loading or reloading (strong axis bending tests)

Joint configuration	$\Delta\theta_1$		$\Delta\theta_2$		$\Delta\theta_3$		$\Delta\theta_4$		k_U		M_u	
	Average (rad)	COV	Average (rad)	COV	Average (rad)	COV	Average (rad)	COV	Average (kN.m/rad)	COV	Average (kN.m)	COV
All types	0.005	1.22	0.035	0.28	0.044	0.50	0.080	0.51	135.55	0.13	3.83	0.09

Table 7 Results of the tensile stiffness for the multilinear model (cuplok joint, tensile tests)

Joint configuration	k_1		k_2		k_3		k_4	
	Average (kN/mm)	COV	Average (kN/mm)	COV	Average (kN/mm)	COV	Average (kN/mm)	COV
All types	3.57	0.91	33.37	0.35	7.76	0.35	2.77	0.63

Table 8 Results of other parameters for the multilinear model (cuplok joint, tensile tests)

Joint configuration	$\Delta\delta_1$		$\Delta\delta_2$		$\Delta\delta_3$		$\Delta\delta_4$		k_U		P_u	
	Average (mm)	COV	Average (mm)	COV	Average (mm)	COV	Average (mm)	COV	Average (kN/mm)	COV	Average (kN)	COV
All types	0.23	1.47	1.39	0.43	3.20	0.66	2.33	1.26	127.85	0.31	70.71	0.16

Table 9 Results of the bending stiffness for the multilinear model of the spigot joint

Load ratio	k_1		k_2		k_3		k_4	
	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV
20%	55.05	0.15	162.40	0.25	55.60	0.72	–	–
50%	–	–	127.92	0.27	39.13	0.26	7.28	0.22
Simple bending	–	–	27.92	0.26	9.50	0.59	2.09	1.11

Table 10 Results of other parameters for the multilinear model of the spigot joint

Load ratio	$\Delta\theta_1$		$\Delta\theta_2$		$\Delta\theta_3$		$\Delta\theta_4$		k_U		M_u	
	Average (rad)	COV	Average (rad)	COV	Average (rad)	COV	Average (rad)	COV	Average (kN.m/rad)	COV	Average (kN.m)	COV
20%	0.005	1.49	0.014	0.28	0.019	1.11	–	–	–	–	–	–
50%	0.000	–	0.017	0.16	0.016	0.31	0.032	0.48	73.93	0.13	3.53	0.09
Simple bending	0.000	–	0.054	0.31	0.044	0.81	0.151	1.48	24.32	0.66	1.79	0.24

Table 11 Results of the bending stiffness for the multilinear model (forkhead joint, bending tests about axis 2)

Load ratio	k_1		k_2		k_3		k_4	
	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV	Average (kN.m/rad)	COV
50%	–	–	29.33	0.19	11.30	0.46	6.68	0.08

Table 12 Results of other parameters for the multilinear model (forkhead joint, bending tests about axis 2)

Load ratio	$\Delta\theta_1$		$\Delta\theta_2$		$\Delta\theta_3$		$\Delta\theta_4$		k_U	
	Average (rad)	COV	Average (rad)	COV	Average (rad)	COV	Average (rad)	COV	Average (kN.m/rad)	COV
50%	0.000	–	0.032	0.36	0.036	0.48	0.042	0.003	21.51	0.45

Table 13 Lower and upper bounds for truncated probabilistic models, cuplok joints locked using a hammer (strong axis)

Bound	$\Delta\theta_1$ (rad)	k_1 (kN.m/rad)	k_2 2L (kN.m/rad)	k_2 3L (kN.m/rad)	k_2 4L (kN.m/rad)	$\Delta\theta_4$ (rad)	M_u (kN.m)
Lower bound	0	0	5	5	5	0	1.5
Upper bound	0.04	60	100	130	150	0,25	5

Table 14 Probabilistic models for selected variables, cuplok joints locked using a hammer (strong axis)

Joint configuration	$\Delta\theta_1$	k_1	k_2 (2L, 3L, 4L)	$\Delta\theta_4$	Mu
All (2L, 3L, 4L)	tNormal	tNormal	tWeibull	tLogistic	tWeibull

Table 15 Parameters of probabilistic models, cuplok joints locked using a hammer (strong axis)

Joint configuration	$\Delta\theta_1$		k_1		k_2		$\Delta\theta_4$		M_u	
Two ledgers (2L)	Mean: SD:	-0.0084 0.0125	Mean: SD:	-13.844 27.043	Shape: Scale:	8.071 75.061	Location: Scale:	0.0232 0.0527	Shape: Scale:	14.795 3.989
Three ledgers (3L)					Shape: Scale:	4.878 90.292				
Four ledgers (4L)					Shape. Scale:	6.189 92.321				