Forth Replacement Crossing – The Independent Structural Design Review Role and Deck Technical Review Methods

Dr Craig Giaccio, Technical Director, Transportation Structures, AECOM UK.

Summary:

The Forth Replacement Crossing, currently under construction in Scotland, United Kingdom, is one of the largest bridges currently being built in Western Europe. It has a total length of 2.5km with cable stayed length of approximately 2km. This paper, prepared by the Independent Design Verifier, presents a summary of the bridge, the requirements of the Independent Verifier in the United Kingdom, the analysis methods used in verification, and provides some updates on construction progress.

The Sofistik software package for analysis of global action effects of the bridge in-service and during construction was a key feature of the analysis procedure used for independent verification. This paper provides a detailed outline of the verification process and how key strengths of the Sofistik package were used in the verification of the bridge.

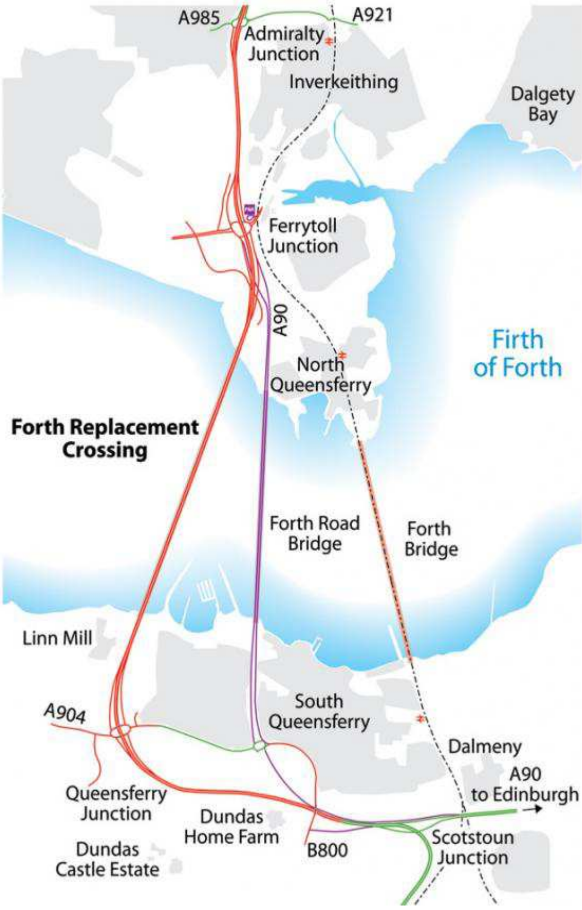
1 INTRODUCTION

The Forth Replacement Crossing, or the Queensferry Bridge, presently being constructed in Scotland, United Kingdom, is one of the largest bridges currently under construction in Western Europe. The construction contract was awarded to a consortium known as Forth Crossing Bridge Constructors (FCBC) which is a joint venture between American Bridge, Dragados, Hochtief, and Morrison.

The bridge design is being undertaken by a joint venture of Ramboll, Leonhardt Andra und Partner, and Grontmij, known as the Design Joint Venture (DJV). The independent verification is being undertaken by a joint venture between AECOM and URS. The bridge is being constructed for Transport Scotland whose technical representative is a joint venture between Jacobs and Arup. The Contract value is £790M.

The Forth Replacement Crossing Contract does not include only the main cable stayed crossing over the Forth Estuary, it includes a significant amount of approach road works and associated bridge structures. The full scope of the work is shown in Picture 1. The AECOM/URS Independent Verification joint venture shared work as follows:

- Main cable stayed crossing – AECOM;
- Approach viaduct to the north of the Cable Stayed Bridge– AECOM;
- Approach viaduct to the south the Cable Stayed Bridge – URS;
- Approach road structures – URS;



FRC Principal Contract	
Contractor	Forth Crossing Bridge Constructors (FCBC)
Designer	Ramboll, Grontmij, Gifford and Leonhart Andra & Partner (LAP)
Checker	URS Scott Wilson & Aecom
Contract Start/End Dates	18 April 2011 - Dec 2016 (68 months)
Contract Value	£790 million

Construction of new cable-stayed crossing across the Forth and connecting roads.

Legend

- New/Improved Roads
- Railway
- Airport
- Railway Station
- Existing Carriageway
- Waterbodies
- Settlements
- P&R Park and Ride
- Proposed Public Transport Links

Image courtesy of Transport Scotland

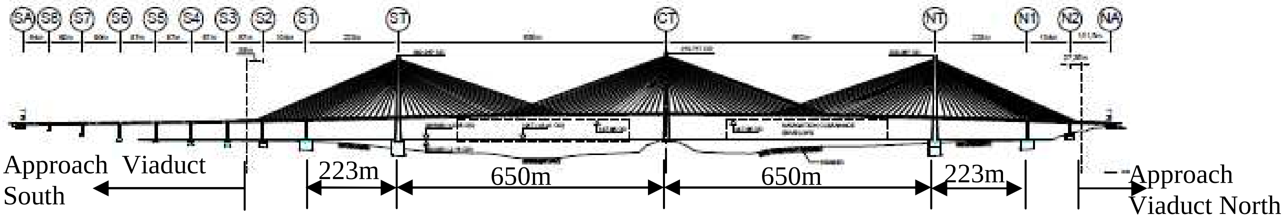
Picture 1 Bridge Location

The main cable stayed bridge global model was modelled in Sofistik by the Independent Verification Engineer, including the erection sequence. This was used as a basis for the detailed independent verification of the main cable stayed bridge.

This paper presents a description of the bridge form, it outlines the responsibility of the Independent Verification Engineer in the United Kingdom, and it outlines the methods of analysis adopted for the Independent Verification of the main cable stayed bridge crossing deck.

2 BRIDGE DESCRIPTION

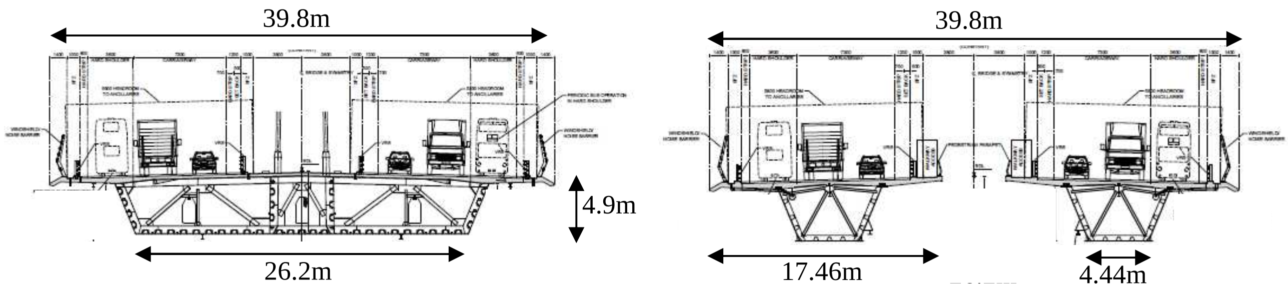
The bridge is 2.539km in length. It comprises three cable stayed spans with maximum span of 650m and a total length of 1.95km. The north and south approach viaduct spans to the cable stayed bridge vary from 65m to 104m.



Picture 2 Bridge Elevation (Image Courtesy of FRC Design Joint Venture and Transport Scotland)

2.1 Deck Superstructure

The deck superstructure comprises two distinct structural forms. The main cable stayed bridge is a single 39.8m wide steel concrete composite cross section. The width of the concrete deck slab is 39.8m, the width of the bottom plate of the composite section is 26.2m. The section comprises two internal webs onto which cables are anchored, termed stay anchor webs, and two outer web panels which close the section for torsional rigidity, termed the inclined webs. The approach viaduct deck cross sections comprise two independent steel composite box sections, one for each carriageway. The deck cross section is approximately 4.9m in depth measured from top of concrete.



Typical Main Cable Stayed Span Cross Section   Typical Approach Viaduct Cross Section

Images courtesy of FRC Design Joint Venture and Transport Scotland

Picture 3 Typical Deck Cross Sections

2.2 Deck Substructure

The cable stayed section of the bridge is supported from three reinforced concrete towers with a height of approximately 210m. The towers are variable section reinforced concrete box sections varying from approximately 5.3mx7.6m at the top of the tower to 14mx16m at the foundation. Each tower is fully fixed at the base of the tower. The deck is integral with the central tower (CT) and free to move vertically and longitudinally at the north and south towers (NT & ST). The towers bear onto underlying rock in the Forth Estuary.

The cables are anchored to the towers via a series of rigid steel anchor beams which are located such that the centreline of their cross section intersects the centreline of the cable. One beam is provided for each pair of cables. The steel sections are anchored to the reinforced concrete tower using a steel plated box section which utilises shear studs to transfer the cable force into the tower.

The tie down sections of the Cable Stayed Bridge and approach viaduct are supported on piers. The piers are twin stem reinforced concrete box sections up to 50m in height. The piers are all founded on spread footings which bear onto the underlying rock in the Forth Estuary.

3 UNITED KINGDOM BD 2/05[1] AND INDEPENDENT VERIFICATION

The United Kingdom Highways Agency (HA) Design Manual for Road Bridges (DMRB) document BD 2/05 [1] outlines the responsibilities for design and design checking for all highway structures. For a very large cable supported such as the Queensferry Bridge, the document stipulates that the design must be subject to a completely independent verification by a separate design organisation. The level of verification is termed a Category III check (or colloquially known as a Cat III Check). The process is underpinned by the principle that the Cat III checker is not to influence the design. In this paper, the term Cat III Check and Independent Verification will be used interchangeably.

The Cat III Check process is commonly implemented on larger structures as follows:

- Design basis documents prepared by designer are issued to Cat III checker;
- Cat III checker undertakes independent verification of these documents based on their interpretation of the codes and best/commonly applied practice;
- The design is developed by the Designer using the agreed design basis;
- Design drawings and specification documents prepared by the designer and issued to the Cat III checker. To enable the checker to undertake a fully independent check, it is imperative that these documents are substantially complete to enable the process. Design calculations are not submitted for checking. This underpins the concept that the Cat III checker is to remain divorced from the design process and not to influence the design;
- The Cat III checker receives the completed design and undertakes their own completely independent design calculations to confirm that the design complies with the codes of practice using their own completely independent methods of analysis;
- Cat III Checker and Designer agree on issues raised during check and design is certified for review by Employers Technical Representative;
- Employers Technical Representative raises comments to implement project technical requirements if any such comments are required;
- Designer amends design, if necessary for Employers Technical Representative comments, and issues design to Cat III Checker for final verification and certification for construction.

This structure is sensitive to wind vibration, hence required a wind tunnel test to ascertain if the natural frequency of vibration could be excited by wind and the range of deflections that could be expected under a range of wind speeds applied at varying directions. For such structures in the United Kingdom, it is common that this study is undertaken by a specialist. The specialist requires relevant structural properties such as overall dimensions, element stiffnesses, and results of an eigenvalues analysis including mode shapes and frequencies. Commonly the wind study is not replicated by the Cat III Checker, but the data provided to the wind specialist by the designer is reviewed by the Checker as is the output of the study. This process was applied to the Forth Replacement Crossing.

4 CABLE STAYED BRIDGE DECK INDEPENDENT VERIFICATION PROCESS

The check process for the cable stayed bridge was undertaken using a three tired analysis process to ascertain principle design action effects in the structure and subsequent calculation of utilisation ratio for each structural element. The stages of analysis were:

1. Determine global action effects using a line beam model of the entire bridge structure. Sofistik was used for determination of global action effects. The global effects were determined using two models:
   a. A completed bridge structure model from which permanent and variable action effects could be determined.
   b. A construction stage model from which governing construction stages could be assessed as well as enabling a check of the staging on the locked in permanent action effects from construction.
2. Apply global action effects ascertained from global models to 3D shell element models of sections of the deck to determine action effects in principle elements, including stiffened steel plates forming the deck box, the concrete deck, and transverse frames. These models were termed ‘semi-global models’;
3. Where required, local areas on the bridge were analysed using detailed 3D shell element models, or sub-models, to ascertain design action effects.

The shell elements models used in Stage 2 were compiled to take account of the following:

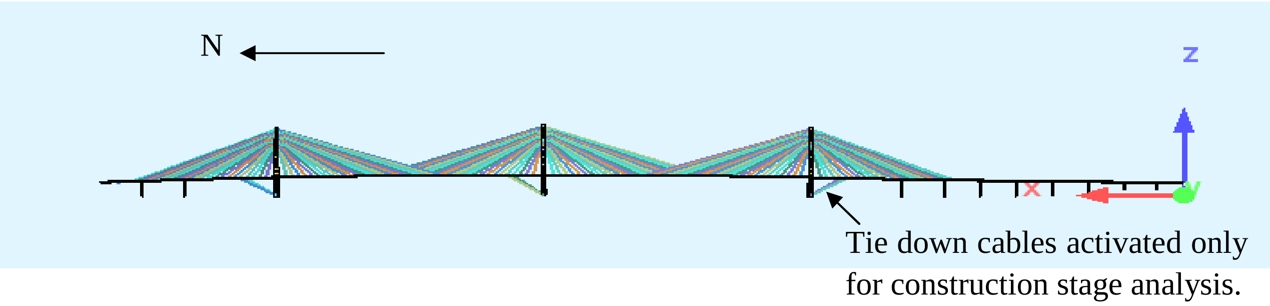
- Shear lag in the region of cable anchors and to determine the distribution of concentrated wheel loads on the deck into the structure;
- Ascertain accurately the distribution of transverse stresses in the composite cross section to accurately assess the utilisation of plated steel panels.

5 THE GLOBAL IN SERVICE MODEL

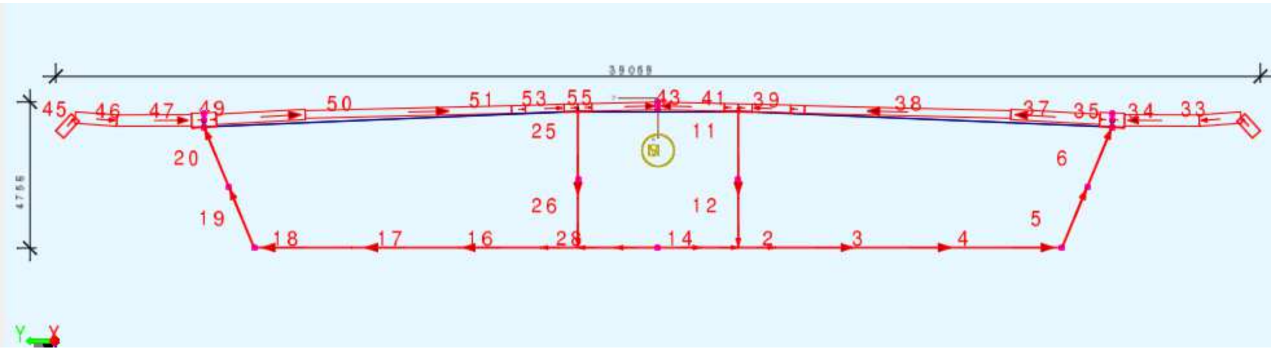
The global in-service model was developed to enable the determination of permanent and transient action effects on the bridge. The primary transient actions are live loads from traffic and wind.

The bridge was modelled using line beam elements with section properties calculated by the Sofistik program based on sectional information input into the model, which were based on the drawings submitted for verification. Picture 4 shows an elevation of the model. Picture 5 and 6 show cross sections of the bridge produced by the program using input data of the cross sections.

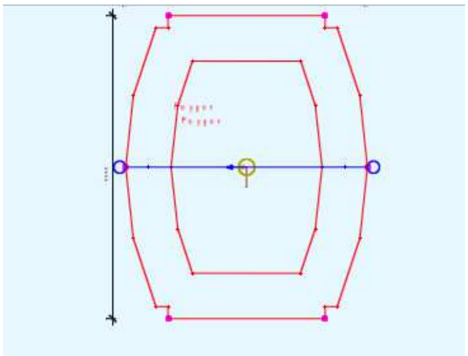
The profile of the bridge was modelled at the design road level for simplicity. To achieve this, cross sections were specified as eccentric to the design road level. This feature in the software automatically positions the centroid of each element at an offset equal to the distance to the centroid from the specified design level. This enabled the changes in the position of the centroid along the length of the bridge to be accurately accounted for. This was a key feature of the model and facilitated determination of changes in the sectional bending moment resulting from the change in centroid at the intersection of deck sections under a large axial force.



Picture 4 Fleshed Bridge Global Model in Elevation



Picture 5 Cable Stayed Bridge Cross Section (Grafix)



Picture 6 Fleshed Tower Section (Grafix)

Where sections tapered, e.g. the towers, the automatic tapering feature between adjoining cross sections was used to ensure that smooth changes in stiffness were calculated throughout the length of the relevant element to accurately determine the stiffness response of the structure.

The cables were modelled using Cabl (cable elements) in Sofistik. The effect of cable sag on the stiffness was modelled using an effective Youngs Modulus calculated as a reduced E value applied to the model.

In place of the ELLA module available for Sofistik, a routine was developed using the MAXIMA routine to find governing live load positions. Loading for each of the scenarios required by BS EN 1991-1-2 [2] and the UK National Annex [3] were applied to short, discrete lengths of the bridge, then combined using the MAXIMA routine to produce the most onerous load effects at a given position on the bridge. This load combination was saved using the CSAV function which enabled the load combination to be factored accordingly for use in the relevant ULS or SLS combinations. The following code illustrates the code for the application of the live load for Load Model 1.

```
#Define LL_Global_Comb_of_LCs
COMB #WCOMB STAN BASE 3800 TITL 'Comb Q LM1 udl for Foundation Loads'

LET#fq    1.0 $ Primary Live Load SLS factor
LET#fa1   1.0 $ Secondary Live Load SLS factor

     LC (8000 8281 1)  TYPE Q    FACT #fq       $ LM1 udl
     LC (8282 8895 1)  TYPE A3    FACT #fq      $ TS

ECHO LOAD,FACT YES
SUPP  ETYP  TYPE  COMB=1 TITL='SLS'

     SUPP COMB #WCOMB EXTR #WEXTR ETYP NODE FROM #ND_ELEMENT TYPE #WTYPE CSAV
#WLCSTORED TITL 'C LL FLM1 udl opt1a for N'#ND_ELEMENT+#WEXTR+#WTYPE ;END

     SUPP COMB #WCOMB EXTR #WEXTR ETYP BEAM FROM #BM_ELEMENT X=0 TYPE #WTYPE
CSAV #WLCSTORED TITL 'C LL LM1 udl for BM'#BM_ELEMENT',x=0,for'#WEXTR+#WTYPE;
END

#enddef $ LL_Global_Comb_of_LCs

#Define Block_Comb
     LET#WCOMB=1 ; LET#WLCSTORED=#WLC
     #Include LL_Global_Comb_of_LCs
#enddef $Block_Comb

LET#WEXTR='MAX' ;
LET#WTYPE='PX'  ;
LET#WLC  141    ;
#include Block_Comb
```

In accordance with Eurocode for composite steel and concrete structures, BS EN 1994-1 [4], the model was analysed under relevant ULS combinations to assess if concrete cracking would occur under any ULS combinations. Two areas of the bridge deck were identified as cracking under certain ULS combinations, hence cracked section properties were used in these areas. An equivalent concrete Youngs Modulus was applied for simplicity, which was prorated to ensure that the axial stiffness (EA) was equal to that of the deck longitudinal reinforcement only in place of the deck concrete.

The bridge has several construction tolerances that required consideration during analysis, including a curved or inclined tower. To assess the impact of this on deck action effects along with the sensitivity of the action effects in the deck to cracked concrete in the towers, a full non-linear analysis was undertaken. Scenarios were reviewed to assess the impact of superimposing credible worst case combinations of the tolerances and non-linearities on deck design action effects. The maximum permitted utilisation of individual deck elements was reduced from 1.0 to cater for potential non-linearities in the structure if appropriate.

6 CONSTRUCTION STAGE MODEL

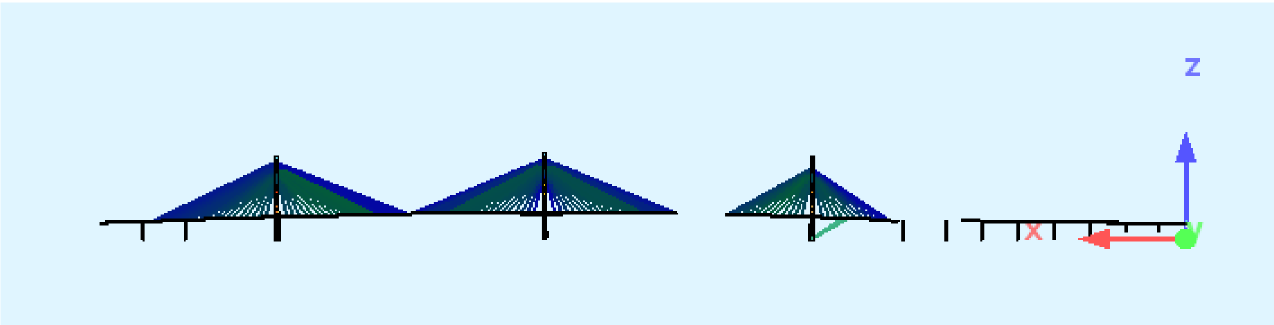
A model that included each stage of the bridge construction was developed for the cable stayed bridge for two purposes:

1. To ascertain action effects on the bridge during each stage of construction;
2. To ascertain if the staged construction sequence modified the permanent action effects in the bridge.

The bridge is primarily constructed using segmental balanced cantilever construction method at each tower fan. Approach viaducts are to be launched into position. Once each fan is erected, and approach viaducts in position, a series of construction stages are to be undertaken to connect each section of the bridge. The staging includes erecting closure segments between balanced cantilevers and horizontal jacking to position approach viaducts for closure. Once the bridge is connected, cross over stays are installed, and a series of stressing operations are undertaken in an effort to reproduce action effects of the bridge in place (without staging effects).

Segments of the bridge are to be lifted from barges in the Forth Estuary using a mobile traveller supported from erected previously installed deck segments. Segments have a self weight of up to 750 tonnes. The erection traveller produces reactions onto the bridge of up to 17.5MN.

The model was developed in the Sofistik Construction Stage Manager (CSM). This feature enabled activation of model elements in a defined sequence corresponding to the proposed construction sequence. The Construction Stage Manager enabled the application of significant loads, such as the erection traveller used for lifting deck segments into position, at relevant stages in the model. The model included circa 650 stages of construction. The model is illustrated in Picture 7.



Picture 7 Elevation of CSM Model during Construction of North Fan from Sofistik Animator

Creep and shrinkage was applied to the deck concrete throughout the staging of construction in order to accurately determine the locked in creep and shrinkage in the bridge once the individual fans were connected to each other and to the approach viaducts.

Certain stages of construction produce limiting design load combinations for certain areas of the bridge. To ascertain ULS combinations it is imperative that the accumulated action effects are determined at the stage of construction under consideration. The Sofistik programme stores the applied loads and results of each stage of construction into a separate file, the *.csmlf file. The CSM module superimposes each of these to produce action effects at each stage. A very useful feature of the csmlf file is that action effects at each stage can be retrieved at a given stage, along with the activated structural elements at that stage to enable superposition of transient loads along with associated ULS factors. An example of code used to determine maximum and minimum ULS combinations for moment about the global y-axis for variation in the ULS factor for permanent action effects is provided below. Addition of transient loads is a simple case of creating relevant loads in Sofiload, including in the ASE program, and factoring accordingly in AQB.

```
#define   cs_design=421              $model stage of interest
#include design_csmlf.dat            $CSM file for superposition
#define c_grp=csmgrp$(cs_design)

+PROG AQB urs:7
   BEAM grp (501 508 1)
   #include aqb_beam_cs                      $  from csmlf file
   #define GAMU_G_1=GAMU 1.32 GAMF 0.95    $  G_1 defined in csmlf file
   #define GAMU_G_2=GAMU 1.32 GAMF 0.95    $  G_2 defined in csmlf file
   #define GAMU_G_3=GAMU 1.32 GAMF 0.95    $  G_3 defined in csmlf file
   #define GAMU_G_7=GAMU 1.05 GAMF 0.95    $  G_7 defined in csmlf file
   #define GAMU_G_8=GAMU 1.05 GAMF 0.95    $  G_8 defined in csmlf file

   #include stage_design  $from csmlf file
   COMB MAXD MY TITL 'ULS_MAX_MY' LCST 981 LC1 G - LC2 C
   COMB MIND MY TITL 'ULS_MIN_MY' LCST 982 LC1 G - LC2 C
   STRE K
End
```

7 DECK SEMI GLOBAL MODEL

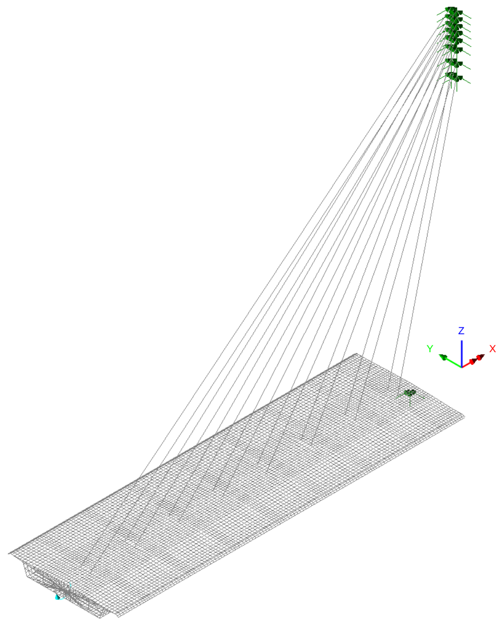
The reduced stress method prescribed in the Eurocode for plated steel elements, BS EN 1993-1-5 [5], was used to calculate the utilisation ratio of each steel deck panel in the bridge. To implement this method accurately, determination of the longitudinal and transverse stresses in each stiffened plate was required to undertake the necessary biaxial stress combinations at ULS to determine the utilisation ratio. This was undertaken using a series of 3D shell element models of discrete lengths of the bridge termed semi-global models. This resulted in the entire cable stayed bridge deck being analysed using 3D shell element models. An illustration of a typical deck shell element model is provided in Picture 8.

These semi-global models provided each checking engineer with an accurate determination of shear lag effects which was of particular interest at the connection points of cables. Local concentrations of forces in the stiffened plates near cable connection points resulted in higher utilisations in certain panels than might be predicted by manual methods of distributing global action effects.

Each semi-global model used the load positions found using the global Sofistik model in order to ascertain stresses in stiffened deck plates and the post-tensioned concrete deck slab. Loads were applied at the boundary of each semi-global model equal to those found from the Sofistik model for the basic load combinations.

For simplicity, the semi-global models were generally fixed at the north end of the section with a component loads obtained from the global model applied at the south end of the model.

Underpinning the semi-global model approach was that the cables were effectively connected rigidly at the towers. This required a method to capture the flexibility of the tower in applying cable forces to the deck and to ensure that the cable stiffness was accurately captured in the deck semi-global models. To implement this, loads were applied to cables via an applied strain, the magnitude of the strain was balanced with the global Sofistik model to achieve equal cable loads under each basic load case considered, and hence balancing loads under each basic load case. As the system is statically determinate, once this load balancing was achieved, the reactions at the fixed end become equal to the nodal action effects determined in the Sofistik model for a given basic load case and the semi-global models produced consistent results with the global models.



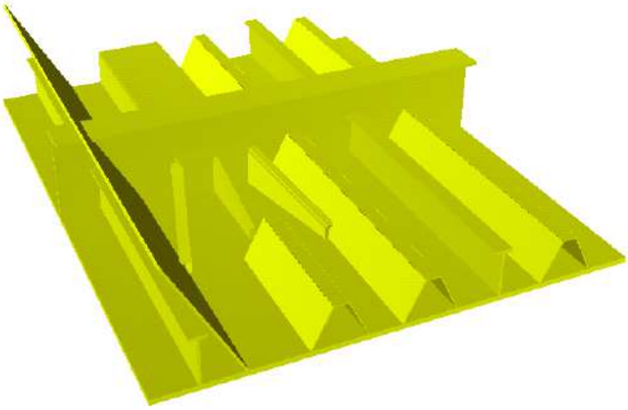
Picture 8 View of Typical Semi Global Model

The shell element models were then used to produce the necessary stresses for each ULS combination which enabled calculation of the utilisation ratio for each deck panel and the deck slab. The semi-global models were sufficiently detailed to permit the determination of forces in transverse cross frames which resulted in the calculation of utilisation ratio of these members and their connections to the primary steelwork being a relatively straight forward exercise.

8 SUB-MODELS

Where required, detailed 3D shell models of local areas were developed to enable an accurate depiction of stresses in local areas. These models were invaluable, particularly for areas around bearings or for stages of construction, such analysing the deck panels supporting the erection traveller whilst a segment is to be lifted during construction.

An example of a sub model used for checking of a temporary stage of the bridge under longitudinal jacking is provided in Picture 9. This was used to validate that the concentration of load applied to the deck by the chosen temporary works system could be accommodated within the deck steelwork as designed for the in-service condition without over-stressing the deck panels.



Picture 9 Sub-model of Steelwork Details on Bottom Plate of Deck

9 PROJECT PROGRESS

2014 is a significant year for the project. Deck steelwork that has been fabricated in China will be shipped to the site fabrication yard for casting of the concrete deck slab and lifting into position. The first shipment of steelwork is expected on site in the near future. The constraints on long distance shipping and site storage are providing FCBC with logistical challenges on site.

The erection of the cable stayed bridge towers is underway, and expedient progress of works at these towers is key for the construction programme. Obviously, deck segments cannot be installed until the towers are at a height to accept the cables required to support the deck during the balanced cantilever erection staging.

Picture 10 shows progress at the time of submission of this paper for acceptance. It includes a photo from the south end of the bridge showing one of the supporting piers on the south approach viaduct with marine works visible in the background. It also includes a photo of a deck segment in the fabrication yard.

Elevation from South end of Bridge

Deck Segment Fabrication

Photo courtesy of Transport Scotland Photo courtesy of FCBC

Picture 10 Site Photos

10 CONCLUSION

This paper has summarised the methods employed by the Independent Verification team (or Category III Checker) of the Queensferry Bridge (Forth Replacement Crossing). It has summarised that the obligation of Independent Verification in the United Kingdom is to validate that the bridge as designed conforms to the codes of practice current at the time of design as augmented by the requirements of the Employers Technical Representative for the particular scenarios not explicitly covered by standards.

The paper has summarised the use of the Sofistik software, which has been the tool that has underpinned the analysis undertaken by the Independent Verifier. This tool has enabled effects of construction staging to be assessed in rigorous detail and has provided a robust method of analysing the effect of creep and shrinkage on this steel composite cable stayed bridge.

11 REFERENCES

[1] *United Kingdom Highways Agency*, BD2/05 Technical Approval for Highway Structures, 2005.

[2] *British Standards Institution*, BS EN 1991-2 Eurocode 1 – Actions on Structures Part 2: Traffic Loads, 2003

[3] *British Standards Institution*, UK National Annex to BS EN 1991-2: 2003 Eurocode 1 – Actions on Structures Part 2: Traffic Loads, 2003

[4] *British Standards Institution*, BS EN 1994-1-1 Eurocode 4 – Design of Composite Steel and Concrete Structures Part 1: General Rules and Rules for Buildings, 2004

[5] *British Standards Institution*, BS EN 1993-1-5 Eurocode 3 – Design of Steel Structures Part 1-5: Plated Steel Elements, 2006