3 Key Issues and Assumptions

In general the key issues and assumptions for the D2M Options are the same as were considered for the Multi-Modal Scheme Assessment. The concepts have been developed with respect to the key issues and criteria which govern the overall design of the bridge. The major design objectives are to provide an elegant, unique and instantly recognisable structure which is durable, straightforward to maintain and embodies the principles of sustainable development. With the procurement cost and programme being key factors for delivery of the project, constructability is also very important as this will lead to a reduced construction period as well as reduced costs.

Aerodynamic stability is an issue whose importance for any long span structure has been well established. Whilst a programme of wind tunnel testing is required to fully investigate these phenomena, the use of correlations established from previous tests has been used to provide preliminary guidance on performance.

An unusual structural feature of the Forth Replacement Crossing is the provision of double main spans which are inherently less stiff than a traditional system where the pair of towers which flank the single main span are anchored back by the stay cables in each side span to these stiffer elements which are connected to the ground. In the case of a double main span, the central tower has no back stays and may deflect significantly under asymmetric loading of the bridge resulting in relatively large deck deflections. This bridge will include the world's longest spans in a multiple span cable stayed bridge and developing an understanding of the flexibility associated with this structural system as well as appropriate mitigation measures has been influential in the structural development.

The bridge crosses a navigable waterway and maintaining safe navigation clearance at all times governs the vertical alignment of the bridge. Furthermore the potential consequences to the bridge due to errant ships impacting the towers and piers are critical to the design of the lower sections of the towers and the foundations. The possibility of subsequent explosions and pool fires if the ships contain hazardous flammable materials is also being studied.

3.1 Crossing Stays

As noted above, a fundamental consideration for the general arrangement of the bridge is the provision of two cable-stayed main spans which requires special consideration of how to stabilise the central tower.

Studies were carried out during the original concept development which indicated that overlapping the stay cables over approximately 25% of the main spans would provide the necessary global stiffness to stabilise the central tower. The crossing stays were adopted for the Three Corridor Option developed for the Multi-Modal Base Case and are retained for the current D2M Scheme Assessment.

For solutions with the stay cables anchored at the outside edges of the deck, the overall deck width must vary to accommodate the anchorages in the zones of overlapping stays. Studies carried out (see Appendix B) have led to solutions with minimum changes in deck width, whilst avoiding any excessive dead areas of unused deck space.

3.2 Consideration of longer main spans

The location of the south tower in deep water has led to previous consideration of main spans longer than the 650 m proposed by the FRCS Reference Design. However, the marine borehole investigation that has now been carried out indicates that rock level at the proposed south tower location is at approximately -40 mOD compared to a previously assumed level of -50 to -55 mOD. This reduces any potential benefit of longer main spans.

A second consideration was the reduced design ship impact forces on the towers and piers associated with longer main spans. This would be due to the towers and piers being further from the typical vessel transit paths. However, results from the ship impact investigations show that the reduced foundation costs would not justify the increased superstructure costs.

Therefore longer main spans are not considered to offer an advantage.

3.3 Live Load

Initial D2M feasibility studies were carried out based on the design live loading developed for the Multi-Modal Scheme Assessment which proposed a reduction in live load for loaded lengths greater than 200 m. This had been determined based on comparing the UK National Annex to the Eurocode with HA loading defined in the DMRB document BD 37 - Loads for Highway Bridges.

However, it was recognised that this comparison was sensitive to the carriageway widths since BD 37 HA loading considers discrete numbers of notional lanes whereas Eurocode National Annex applies a uniform pressure loading to the carriageway.

For the carriageway widths associated with the D2M functional cross sections it has been found that it is reasonable to apply the UK National Annex loading without modification. Therefore this is the live loading adopted for the Scheme Assessment studies documented in this report.

3.4 Ship Impact

The bridge crosses a navigable waterway with approximately 5,500 significant vessel transits per year in the Forth Deep Water Navigation Channel travelling to and from Grangemouth and other upstream ports. Vessels up to 39,000 DWT (dead weight tonnes) pass under the bridge but the number of passes of such large vessels is very low. Over half of the vessel traffic is less than 6,000 DWT and only 1% of the traffic is larger than 20,000 DWT. The Rosyth Navigation Channel also passes below the northern main span of the bridge but the volume of shipping using this channel is significantly lower than the Forth Deep Water Navigation Channel.

The importance of ship impact loads for the design of the foundations was recognised during the Setting Forth studies which recommended a design ship impact load of 130 MN based on a 33,000 DWT ice strengthened tanker travelling at 12 knots. However, the Eurocode incorporates more recent research into bow impact forces and would require an impact load of approximately 205 MN for this design scenario. A force of this magnitude would govern the design of the foundations and would require significantly more piles than are needed to resist the ordinary in-service loads of self-weight, traffic and wind.

Considering the very low volumes of large ships it is likely that a statistical analysis would conclude that the probability of a large vessel striking one of the towers or piers at full speed is extremely low, and therefore an acceptable risk, such that the design ship impact scenario could involve a smaller, more typical, vessel and/or travelling at a lower speed. The American design standard AASHTO provides a detailed and prescriptive methodology for carrying out such a statistical analysis which would result in a design impact load of approximately one third that recommended by the Setting Forth studies.

Some of the target criteria, correlations and formulae used by the AASHTO method are superseded by guidance in the Eurocode and recent research. The Eurocode, however, does not provide a prescriptive methodology for the statistical analysis. A project specific statistical methodology is currently being developed which is compliant with Eurocode but includes some of the statistical components of the AASHTO methodology where they are deemed to be relevant. The method also accounts for the complex layout of the navigation channels in the Firth.

An important component of the statistical analysis is the probability that a ship will lose control in the vicinity of the bridge. Loss of control can be to the result of both human error and mechanical failure and the probability of these incidents occurring can be significantly reduced by piloted and tug-assisted vessels. Discussions have been held with Forth Ports which indicate that high rates of pilotage and tug-assistance are expected for the larger vessels and this has been included in the statistical analysis.

3.5 Other Issues

3.5.1 Stay cable type

Two different types of stay cable system are suitable for large cable-stayed bridges: parallel wire cables or multi-strand cables. Alternative cable types of locked coil strand or spiral strand are not appropriate due to their poor fatigue performance, low stiffness and lesser ultimate tensile strength (in typically manufactured cable sizes).

Parallel wire cables have a very compact cross section and are factory manufactured to the specific lengths required. Galvanised wires are arranged into the required pattern, and a polyethylene sheath is extruded onto the outer surface. The cables are wound onto reel and transported to the bridge site, where substantial lifting equipment is required to handle them. Very large jacks are needed to stress the cables. Cable length adjustment can be made with either shim plates, or a large nut on the threaded portion of the cable socket, depending on the system adopted.

Multi-strand cables are assembled on site. After the cable sheath is placed between the tower and deck anchorages, individual strands (each consisting of 7 galvanised wires within a polyethylene sheath) are fed through and secured using wedges at each end. The diameter of the cables is larger than for parallel wire cables of the same capacity, as each strand has its own corrosion protection sheath, and spare space is required within the outer sheath to allow strand installation. Stressing of individual strands can take place using small stressing equipment to adjust the lengths, and care must be exercised to ensure an even force distribution between all strands. Any de-stressing must be done using a large stressing jack to adjust a nut on the anchor so as to avoid disturbing the wedges holding the individual strands.

Cable replacement for parallel wire cables involves removing the entire cable, and replacing it with another one. Large lifting and stressing equipment is required. For multi-strand cables it is possible to withdraw, inspect and replace individual strands by reversing the assembly method. Although still a major operation, it can be performed using relatively small equipment and without major disruption to operation of the bridge. In practice it may be that once the cables have reached the end of their design life, removal of the entire cables may be required which would involve similar procedures as for the parallel wire cables. Nevertheless, the ability to inspect individual “witness” strands at periodic intervals is a definite advantage.

The compact nature of the parallel wire cables enables equipment to be clamped onto the cables at any location along its length. If either cross–ties to link stay cables together, or external damping devices are required to limit unforeseen vibrations, or if street lighting equipment is to be suspended from the stay cables this can be an advantage. For multi-strand cables, provision for these types of equipment must be planned in advance of installing the stay cables and a special fixing point formed in the outer sheath.

At this stage, multi-strand cables appear favourable, due to long term inspection and replacement considerations. As the cable diameters, and therefore wind loading, are larger for this system, designing the structure accordingly does not preclude the use of parallel wire cables if they prove more advantageous. For example it could be considered to tender the project allowing either stay type in order to obtain the most competitive price.

A maximum cable size of 127 strands has been assumed, as although some cable manufacturers include larger cable sizes in their literature, experience and suitable equipment for fatigue testing and installation is extremely limited. There are a number of manufacturers that have a stay system with this size as their limit. If larger sizes are demanded there may be a restriction to competition.

3.5.2 Surfacing thickness

The road surfacing system adopted will depend on the structural nature of the deck. Generally thinner surfacing is used for steel structures compared to concrete or composite structures because of the significant weight saving and hence reduction in structural quantities. In the past very thin surfacing systems have been adopted in the UK with a 38 mm mastic asphalt system being used on a number of steel bridges but this has in some cases resulted in poor ride quality and difficulties in maintaining the system. If an orthotropic steel box girder is adopted, a surfacing thickness of approximately 70 mm will be suitable on top of the stiffened steel deck plate which is consistent with European practice for steel bridges. This thickness will result in reasonable ride quality and allow the upper wearing course to be replaced without disturbance to the lower base course. 70 mm of surfacing also allows a 2 mm reduction in the deck plate thickness compared to thinner surfacing due to composite action in reducing fatigue stresses. An assessment will be made of the most suitable material to use considering Gussasphalt, mastic asphalt or epoxy asphalt systems on top of the waterproofing layer.

For a concrete deck slab, as would be adopted for a composite deck solution, the weight penalty associated with thicker surfacing is proportionally less and a standard 125 mm surfacing layer has been assumed in this assessment (hot rolled asphalt or stone mastic asphalt wearing course with appropriate base layer). This may result in a slightly better ride quality and more standard maintenance and replacement procedures.

3.5.3 Vehicle Restraint Systems and Parapets

Along the edges of each carriageway, vehicle restraint systems will be provided in accordance with the relevant standards. A zone immediately behind each barrier will be kept free of any structural components, so that in case of an accident which leads to deformation of the barrier, the risk of a vehicle striking the structure is extremely small. Nevertheless, vehicle impacts on the structure will be considered in the design. The barriers systems adopted will have been proven to comply with the relevant standards and appropriate limits of deformation.

3.5.4 Windshields

Due to the critical function of the bridge as a key link in Scotland's transport network, it is important that it remains operational at all times for traffic use. The exact criteria for the maximum wind speeds across the carriageway will be defined as part of a study of other major bridge crossings, and research into the effects of gust wind on road vehicles. The criteria will need to be met under all wind conditions when traffic can still use other parts of the network such as the approach roads leading to the bridge. Wind screens will be provided on the bridge to achieve this.

Additional windshields (or modifications to the typical windshields) may be required along short lengths close to the towers, where sudden changes in cross wind can occur due to the shielding nature of the tower structure.

Although footways are not provided for the D2M scheme, the windshields along the edges of the deck will be designed to be difficult to climb over to deter anti-social behaviour.

Possible layout of anti-climb windshields