Appendix B - D2M Feasibility Studies

B.1 Range of Options Considered for Feasibility Studies

The range of options considered for the initial feasibility studies are shown below. Many permutations of options are implied by the table and an initial sifting exercise was carried out during the D2M Concept Workshop held on 22nd August 2008 in order to draw up a short list of nine options for development to DMRB Stage 2 Scheme Assessment.

Functional Cross Section	**Two Corridor**			**Single Corridor**	
Tower Form	Mono-Tower Split Tower, Narrow Tower			H-Shape Tower Diamond Tower	
Deck Type	Single Deck Box Girder Orthotropic, Composite Shape A, Shape B	Twin Deck Box Girder Orthotropic, Composite	Twin Deck Ladder Beam Composite Box Beams, Plate Girders	Single Deck Box Girder Orthotropic, Composite Shape A, Shape B, Shape C	Single Deck Ladder Beam Composite Box Beams, Plate Girders
Stay Anchorage Location (on deck)	Central	Edges Combo	Edges Combo	Edges Central	Edges

B.2 Short List of Options Considered for Stage 2 Scheme Assessment

Option	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Functional Cross Section	Two Corridor					Single Corridor			
Tower Form	Narrow Mono-Tower					H-Shape Tower		Diamond Tower	
Deck Type	Orthotropic Single Deck Box Girder	Composite Single Deck Box Girder	Orthotropic Twin Deck Box Girder	Composite Twin Deck Ladder Beam (Box Beams)	Composite Twin Deck Ladder Beam (Plate Girders))	Orthotropic Single Deck Box Girder	Composite Single Deck Box Girder	Composite Single Deck Ladder Beam (Box Beams)	Composite Single Deck Ladder Beam (Plate Girders))
Stay Anchorage Location (On Deck)	Central		Edges			Edges			

B.3 Initial Sifting Exercise

The purpose of the initial sifting exercise was to allow more detailed investigation of favourable concepts including calculation of structural quantities for cost estimation. At the time that the initial sifting exercise was carried out it was recognised that some variations of these concepts, not short listed at this stage, could be investigated at a later date if the concept is developed to DMRB Stage 3. Notable examples of this include:

- Twin Box Girder – only an orthotropic version is studied for the Stage 2 Scheme Assessment, a composite version could be studied at Stage 3 with a view to tendering with an open choice of material type.
- Single Box Girder – only Shape A is studied for the Stage 2 Scheme Assessment, Shape B could be studied at Stage 3 with a view to determining which shape is the most favourable.

B.4 Feasibility Studies

The initial sifting exercise considered the output of a number of feasibility studies which were carried out prior to the D2M Concept Workshop. These studies are summarised in the following sections and comprise:

- Cable layout of edge anchored cables
- Feasibility of incorporating a slot into the Mono-Tower
- Provision of torsional restraint at the flanking tower
- Single box girder studies (deck form, torsional behaviour & central cable planes)
- Twin box girder studies (tower form and stay arrangement)
- Ladder beam studies (stay arrangement)
- Aerodynamic implications of interaction between deck and tower modes

B.4.1 Cable layout of edge anchored cables

A zone is required within the width of the deck for the stay cables but due to the crossing stays the overall width requirement for these zones varies along the length of the bridge.

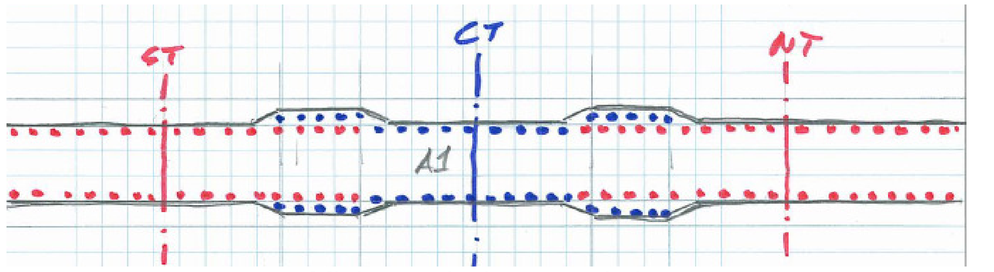
In the mid-span regions, cables from both the central and flanking tower must be accommodated, so a wider zone is required than for just a single plane of cables. A transverse spacing of 1.0 m between the crossing cable planes is assumed which is expected to provide sufficient space for:

- Cable oscillations to occur without collision
- The possibility of cable anchorages either side of a common web
- Travelling of a cable inspection unit

A narrower spacing could be achieved by fixing the cables at their crossing points with a cable clamp. However, this introduces an additional maintenance item (the clamp) at a difficult to access location and also prevents an inspection unit travelling along the cables. Therefore the wider spacing is adopted at this stage.

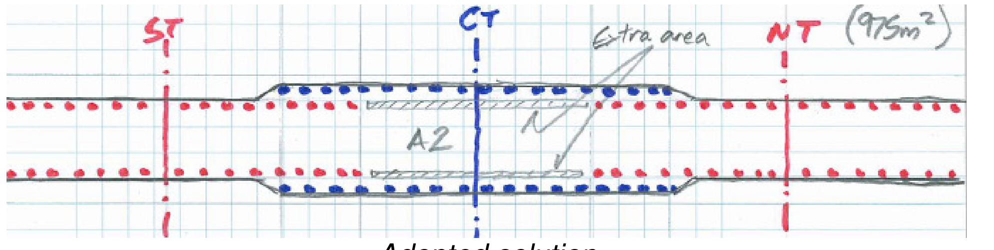
The issue of a wider structural zone can be overcome for some of the solutions by anchoring cables on the inside edges of the carriageways, rather than on the outside edges. For schemes with all cables on the outside edge, transitions are required to change the overall width of the deck.

The minimum deck area solution that could be adopted is illustrated in cartoon form below. However, this option would have the central tower cable fans staggered out of plane in the crossing region which would be very detrimental to the aesthetics.



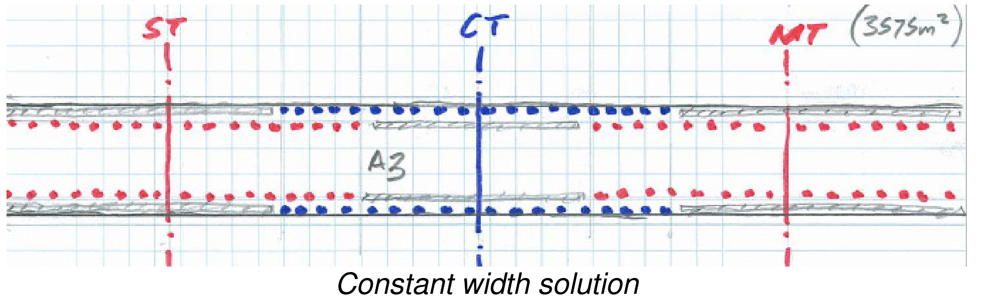
Minimum deck area solution

The solution which has instead been adopted is to have the central tower cable fans in plane but outside of the flanking tower fans. This results in a modest increase in deck area (975 m^2) which is justified by the significant improvement in aesthetics.



Adopted solution

The solution of keeping the deck width constant was also considered as illustrated below. However, this solution requires an increase in deck area of 3,575 m^2 compared to the minimum area solution, over three times the increase required for the adopted solution. This option was therefore rejected on cost grounds since the additional aesthetic benefit of a constant deck width is small.



Constant width solution

B.4.2 Feasibility of incorporating a slot into the Mono-Tower

For the mono tower solutions, the width of the tower at deck level is a critical parameter for determining the structural zone required between the carriageways. This affects the deck width (and therefore the cost) as well as the feasible separation of the stay cables which has implications for the torsional behaviour of the deck.

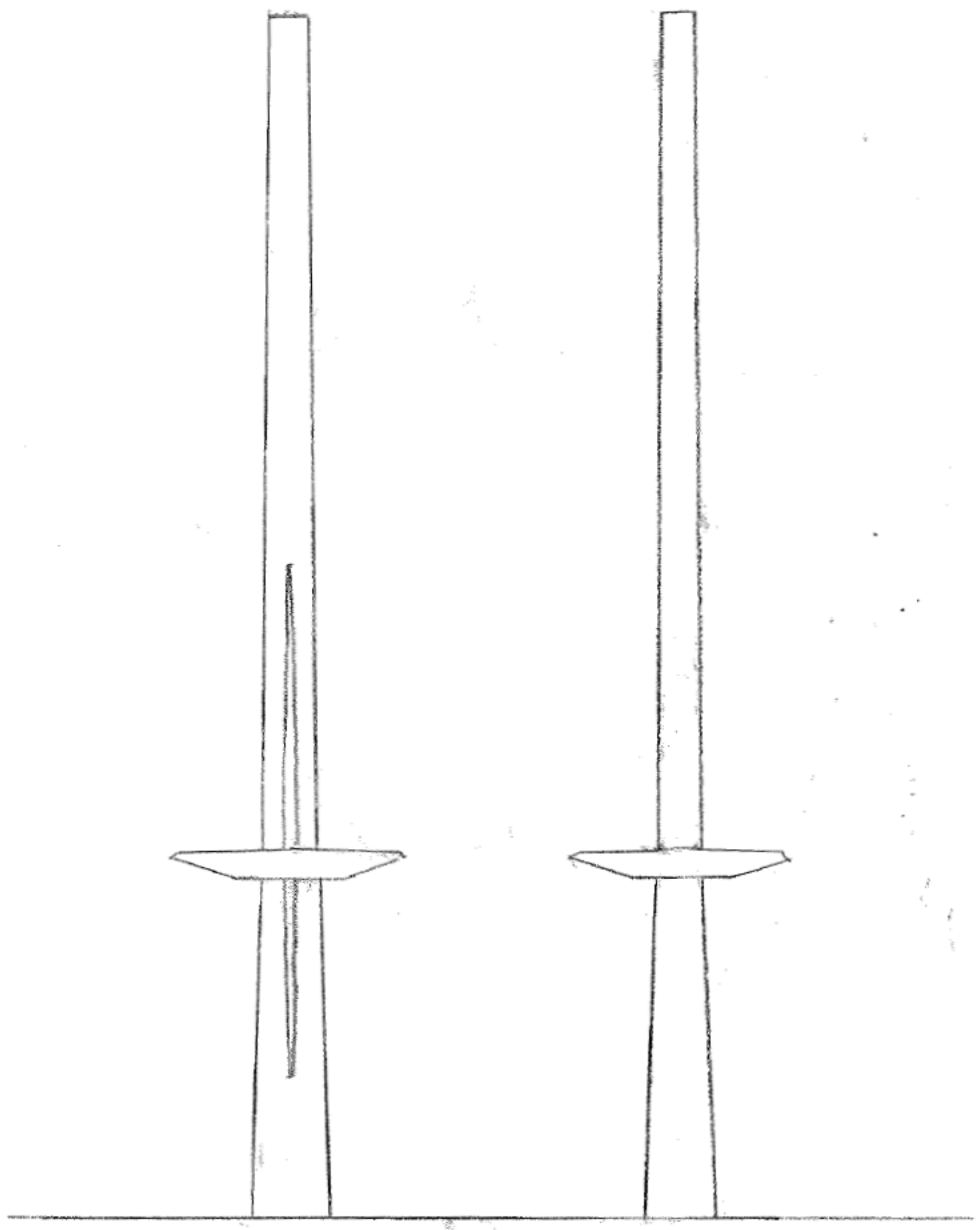
Two tower widths have been considered:

- 9.0 m
- 7.0 m

For the 9.0 m tower, studies have been made on whether it would be possible to provide a vertical slot. The motivation for the slot is both architectural and practical. It will break up the large face of the tower and will also provide a potential access route along the centre of the bridge conveniently located adjacent to the stay cables.

The slot has been found to be practical given reasonable proportions and this solution could be pursued. Although only one particular slot geometry was analysed and verified it is indicative that alternative slot geometries could also be feasible.

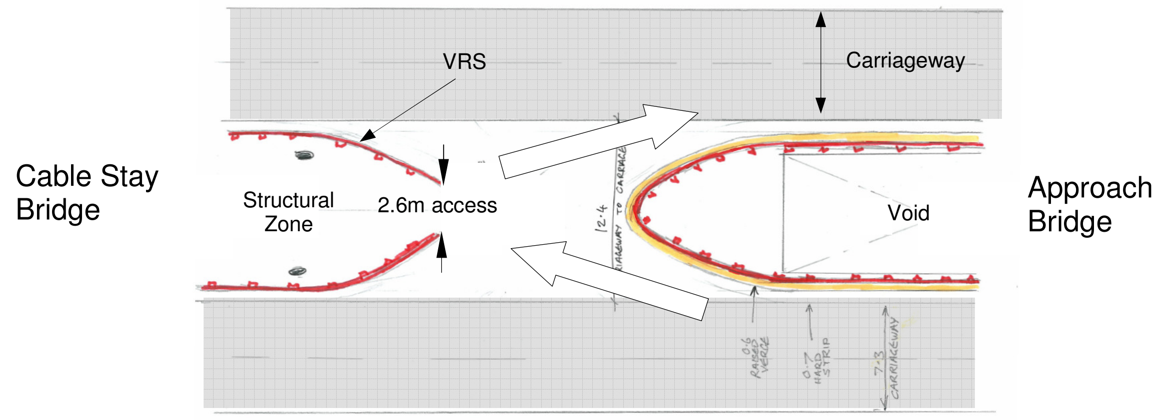
The 7.0 m tower investigations have focussed on determining the minimum width that is practical both structurally and considering the required space for access within the tower. As described in Section 6.2.2, for such a narrow width, slenderness effects and wind buffeting loads become dominant issues which require complex analysis. At this stage preliminary investigations have been made which indicate the 7.0 m dimension to be feasible. The narrow dimension is assisted by the near verticality of the stay cables in the transverse direction which allows for a narrow anchor box in the upper part of the tower.



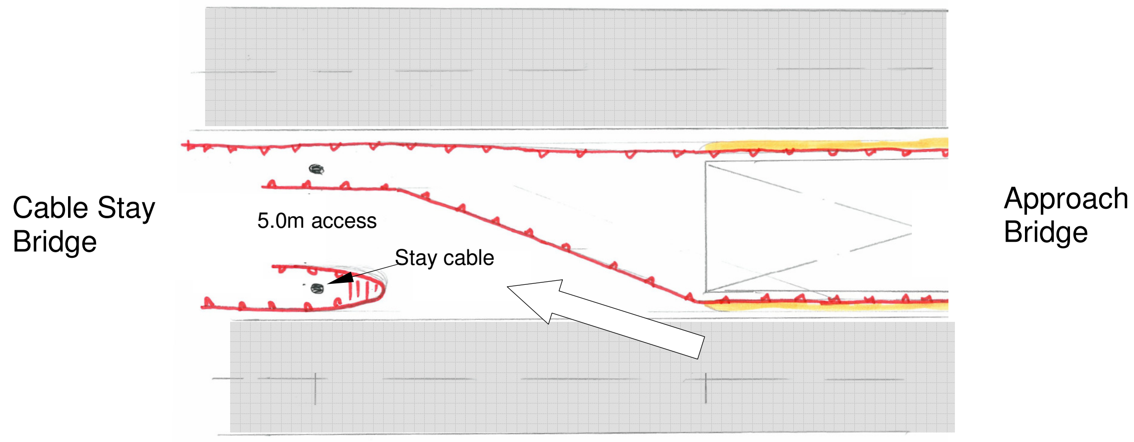
9.0m slotted tower 7.0m narrow tower

Tower forms considered in analysis and verification

Two conceptual arrangements for gaining access to the maintenance space provided by the slotted tower have been drawn up. For the 9.0 m slotted tower, the space between the offside VRS's is 10m at cross sections away from stay cables which would allow the anticipated sizes of maintenance vehicles to turn around. Thus if two way access is provided the access is only required at one end.



Access with crossover – two way - only required at one end



Access without crossover – one way - required both ends

B.4.3 Provision of torsional restraint at the flanking tower

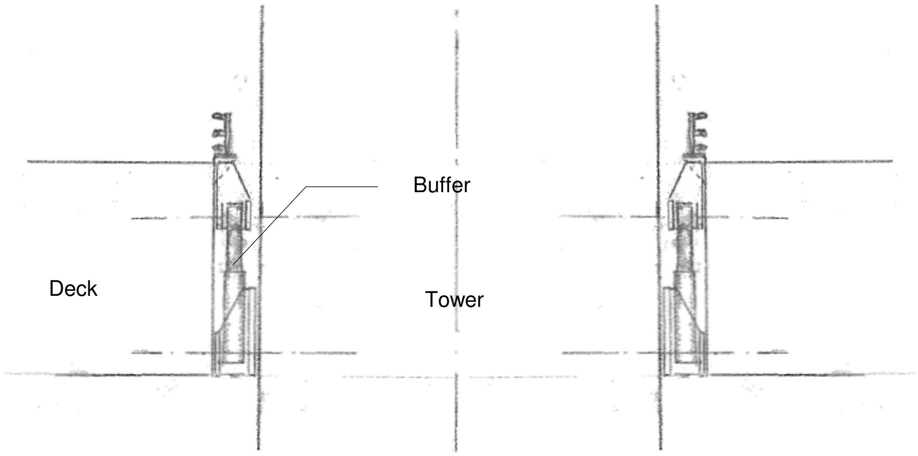
For the flanking towers three different articulation options are considered:

Articulation	Lateral Wind Bearings	Effect of Torsional Restraint	Number of vertical buffers per tower
Floating connection	✓	None	0
Dynamic torsional connection	✓	Improved aerodynamic stability	2 x 1 = 2
Static torsional connection	✓	Reduced deck twist under eccentric traffic load Improved aerodynamic stability	2 x 2 = 4 or 2 x 4 = 8

The floating connection would be as per the Needle Tower with lateral wind bearings between deck and tower but with the deck vertically and longitudinally free.

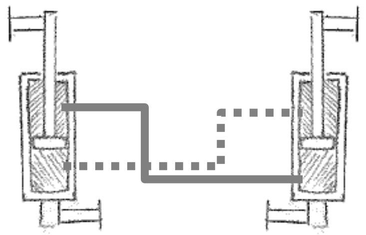
If torsional connection is required at the tower then it is proposed that this is achieved by vertical buffers arranged to provide torsional restraint only. The advantages of buffers are:

- Uplift associated with bearings is not a concern
- Thermal forces and portal frame forces associated with a monolithic connection do not occur
- Permanent loads in the buffers is zero so removal for maintenance and replacement is straightforward
- No loading is transferred to the buffers due to creep and shrinkage of the tower



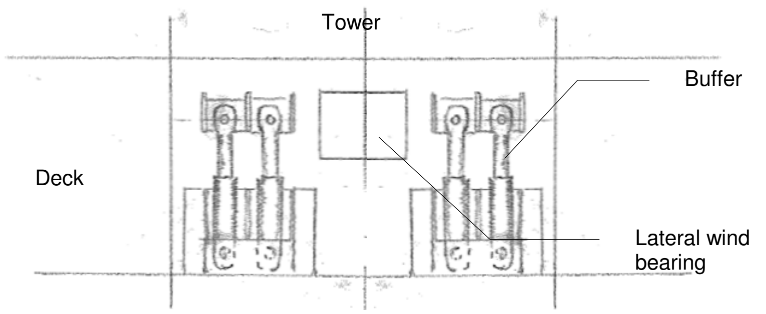
Cross section showing buffer arrangement at flanking tower (looking along axis of bridge)

Restraint can be either static or dynamic depending upon the hydraulic arrangement. Static restraint is achieved by linking the positive and negative chambers of the buffers on either side of the tower. Dynamic restraint is achieved by providing bleed valves to allow only slow movement of the buffer (i.e. the buffer is a Shock Transmission Unit).



Hydraulic linkage for static torsion restraint (schematic)

For buffers providing static restraint the estimated design load in each buffer set due to eccentric traffic loads is 30 MN (for the 9.0m wide tower). This could be distributed as 2 × 15 MN or 4 × 7.5 MN. The dynamic forces from wind buffeting have not been evaluated but it is assumed that these would be less.

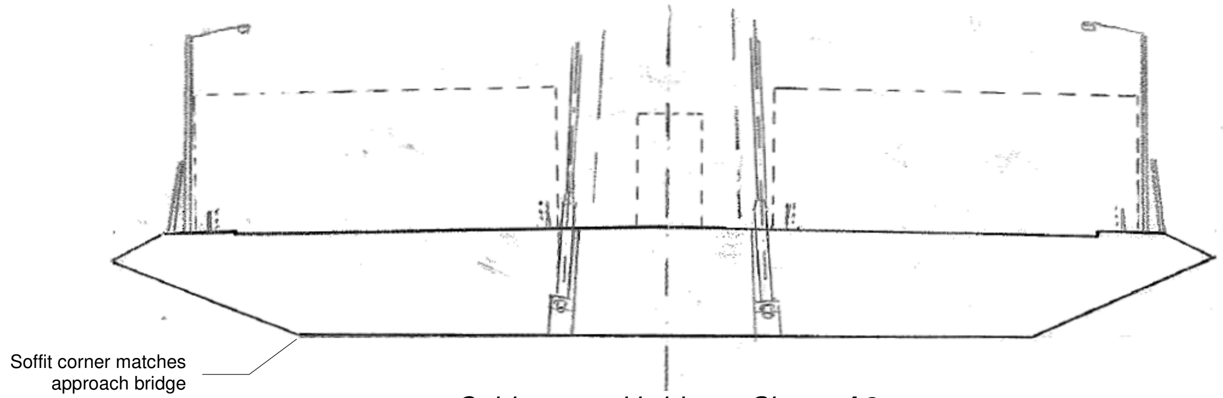


Four buffer set to reduce individual loads (looking transverse to axis of bridge)

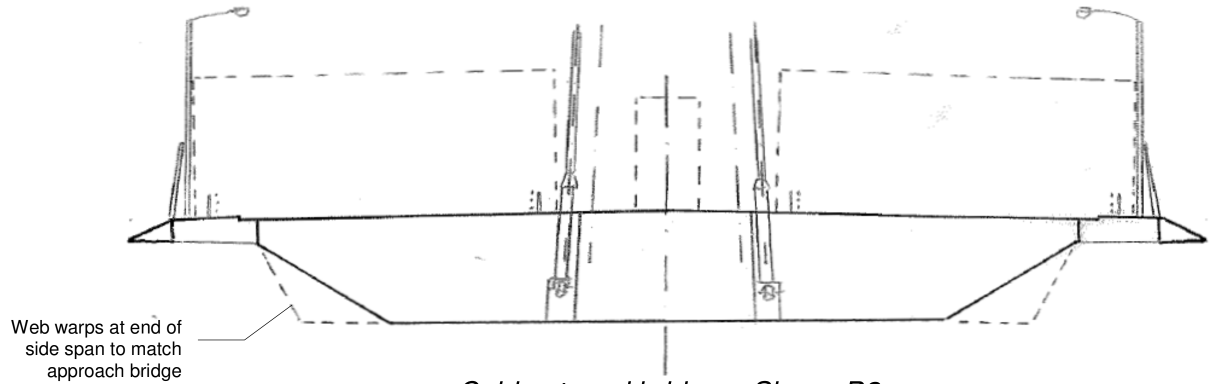
B.4.4 Single box girder studies (shape)

(a) Deck form to suit Two Corridor layout

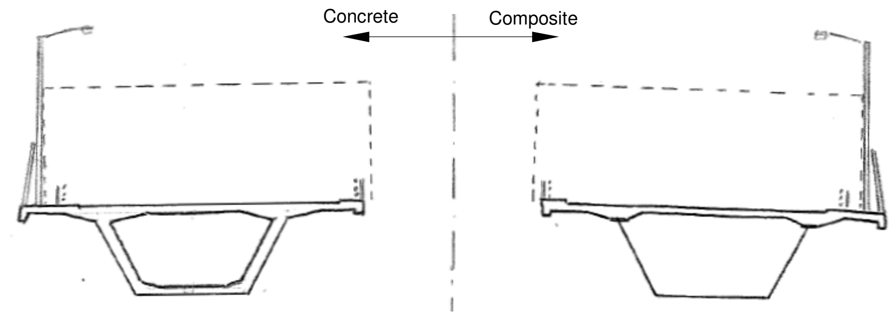
Two alternative cross section shapes are considered for the cable stayed bridge. Both shapes could be achieved in either orthotropic or composite construction. The shapes have been selected to provide visual continuity with a conventional twin box approach bridge of either concrete or composite construction.



Cable stayed bridge – Shape A2



Cable stayed bridge – Shape B2



Assumed approach bridge
(split section showing both concrete and composite alternatives)

Shape A2 is a conventional streamlined box girder shape. Some continuity with the approaches could be achieved by matching the soffit corner. However the shape would still be quite different and it may be worth investigating the cost-benefit of some shaping of the approach viaduct to provide better continuity.

Shape B2 has a reduced size of enclosed box with cantilevers to match the shape of the approach bridge. This solution was adopted on Shenzhen Western Corridor where twin box girder approaches met a wide cable stay bridge deck. Good visual continuity was achieved as illustrated below.

Shenzhen Western Corridor

Parameter	Shape A2	Shape B2	B / A
Orthotropic Deck			
Steel Quantity (kg/m^2)	400	370	93%
J (m^4)	13.2	10.2	77%
Ixx (kNm^2/m)	31,000	24,300	78%
(J / Ixx)$^{0.5}$	0.0206	0.0205	99%
Composite Deck			
Steel Quantity (t/m)	220	190	86%
J (m^4)	18.2	14.4	79%
Ixx (kNm^2/m)	54,200	46,400	86%
(J / Ixx)$^{0.5}$	0.0183	0.0176	96%

A comparison is made of the critical deck properties. Preliminary estimates of steel quantities are expected to be less for Shape B2 but it has a reduced torsional stiffness for the same structural depth, which would lead to higher twists under eccentric traffic loads. An increased structural depth could reduce the twist.

Shape B2 has a reduced mass moment of inertia which means that the effect of the reduced stiffness on the critical torsional frequency may not be very significant.

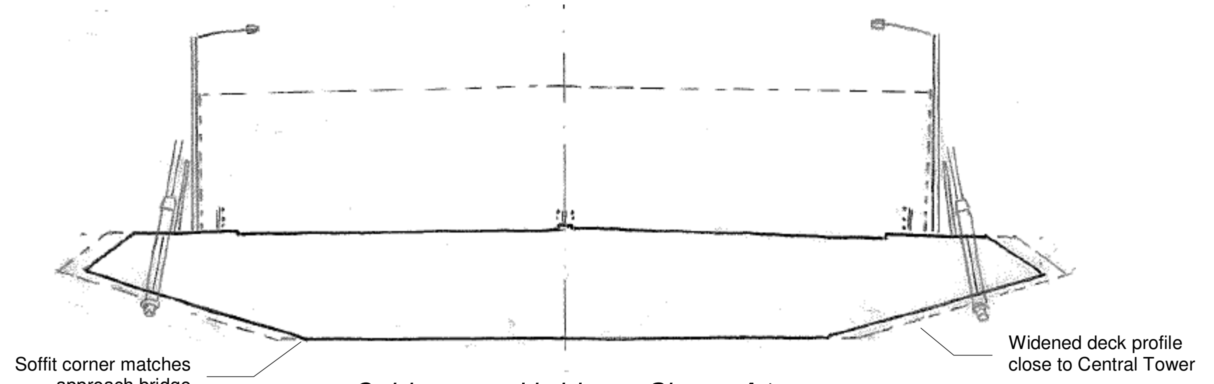
The parameter $\sqrt{\frac{J}{I_{xx}}}$ is calculated as a proxy for $\sqrt{\frac{k}{m}}$ which is proportional to frequency.

This indicates that the reduction in torsional frequency for Shape B2 should be less than 5% for the composite box and negligible for the orthotropic box.

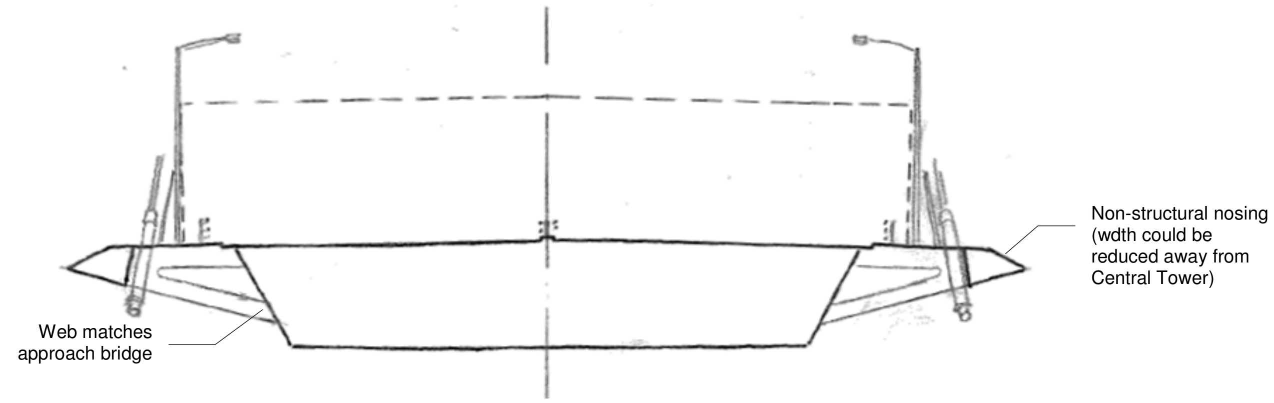
Wind tunnel tests carried out during the preliminary investigations for Storebaelt included sections similar to both shapes and indicated that similar critical wind speeds might be achieved (with all other parameters being equal). However, the aerodynamic performance of either shape needs to be established by wind tunnel tests including the windshield.

(b) Deck form to suit Single Corridor layout

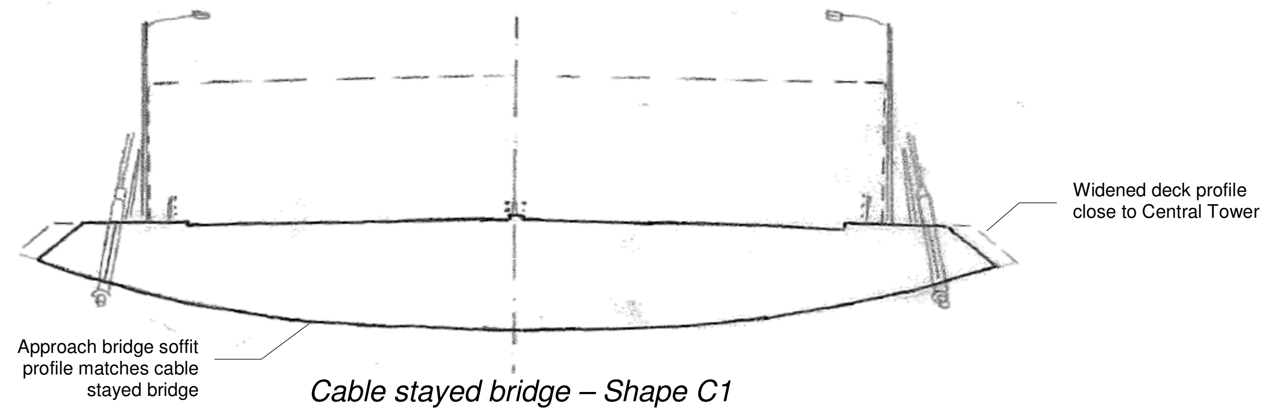
Three alternative cross section shapes are considered for the cable stayed bridge. All shapes could be achieved in either orthotropic or composite construction. Shapes A1 and B1 have been selected to provide visual continuity with a conventional twin box approach bridge of either concrete or composite construction. Shape C1 is a more formed shape for the cable stayed bridge which would be best suited to a multi-cellular single box approach bridge.



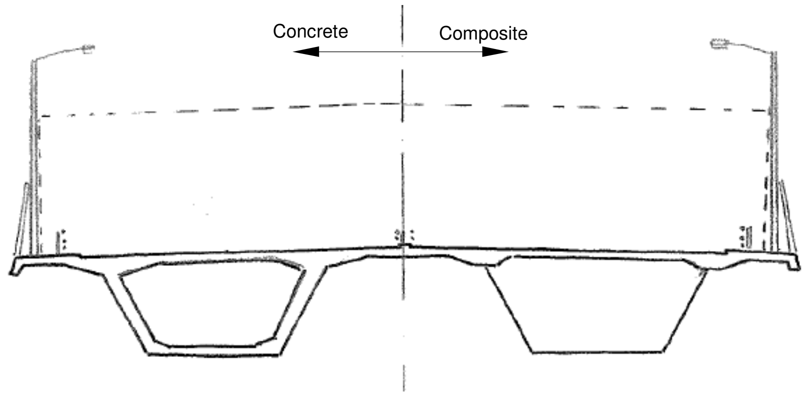
Cable stayed bridge – Shape A1



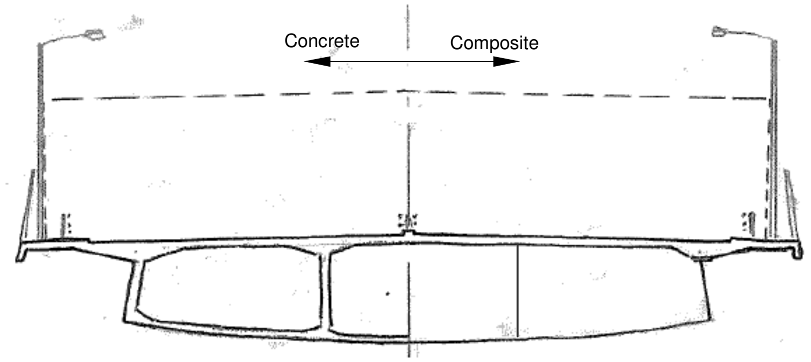
Cable stayed bridge – Shape B1



Cable stayed bridge – Shape C1



Assumed approach bridge for Shapes A1 and B1
(split section showing both concrete and composite alternatives)



Assumed approach bridge for Shape C1
(split section showing both concrete and composite alternatives)

B.4.5 Single box girder studies (torsional behaviour)

The study of torsional behaviour of the single box girder has been focussed on the Two Corridor option since the aim is to anchor the stay cables close to the centreline of the bridge.

A base case structural configuration was analysed and then a number of parameters were varied. The base case was:

- Construction Material: Orthotropic or Composite
- Cross Section: Shape A2
- Structural Depth: 4.365 m
- Restraint at Central Tower: Monolithic
- Restraint at Flanking Towers: Torsional
- Composite Deck Transverse Prestress: Yes
- Tower Type: Slotted 9.0m

(a) Static serviceability

The static serviceability was assessed to determine the maximum deflections and twists that could occur in the bridge deck due to traffic load. The twist is the change in transverse gradient of the bridge at mid span. Characteristic values are tabulated below (nominal 1 in 1,000 year return period).

Configuration	Maximum Deflection (one span only loaded)	Maximum Twist
Orthotropic Deck	3,350 mm	3.6 % (Shape A)
Composite Deck	2,500 mm	2.7 % (Shape A)

Note: Torsional restraint assumed at flanking tower

The maximum vertical deflection only occurs when one of the main spans is fully loaded and the other is fully unloaded. The chance of this occurring is very low and the maximum deflection is expected to have negligible chance of occurring during the design life of the bridge. The maximum twists given are more realistic since commuter traffic could realistically result in one motorway carriageway being fully loaded whilst the other carriageway has little or no load on it. However, the maximum twists do assume the heaviest loading in what will be the hardshoulder for the D2M configuration, therefore the twists are only realistic for contra-flow usage. The long return period associated with characteristic loading must also be emphasised – these deflections are not expected on a routine basis.

Serviceability criteria for twist are rarely given in design standards or even project specific design criteria. The criteria for this project need to be established. However, by making reference to the Messina Bridge design criteria a maximum characteristic twist of 5% is proposed in the draft design criteria for this project.

(i) Contribution of stay cables

For the 9.0 m tower, the flanking fan stay cables are anchored at a transverse spacing of 8.5 m with the central fan stay cables anchored at a spacing of 6.5 m. The stays are still expected to provide some contribution to the torsional stiffness even at this relatively narrow spacing. An analysis was carried out with the spacing of each fan reduced by 5.5 m which represents the closest the cables could be anchored along the centreline. The static twists which result are:

Configuration	Orthotropic Deck	Composite Deck
Design stay cable spacing	3.6 %	2.7 %
Narrow stay cable spacing	4.2 %	3.0 %

Comparison of maximum twist for different configurations

The twist is increased by 10%-15% with the narrower stay spacing. Based on this result it is determined that moving the stays to the extreme edge of the central structural zone is beneficial to the behaviour of the bridge but not essential provided that there is torsional restraint at the flanking towers. Additional studies showed that when the connection at the flanking tower is floating the wide stay cable spacing becomes more critical (35% variation between design spacing and narrow spacing).

(ii) Benefit of torsional restraint at flanking tower

Configuration	Orthotropic Deck	Composite Deck
Torsional restraint	3.6 %	2.7 %
Floating connection	4.9 %	3.6 %

The twist is increased by 35% with the floating connection.

(iii) Effect of deck shape

Configuration	Orthotropic Deck	Composite Deck
Shape A	3.6 %	2.7 %
Shape B	4.5 %	3.2 %

As anticipated the deck twists are higher for Shape B. However, the twists remain within the proposed limit of 5.0%.

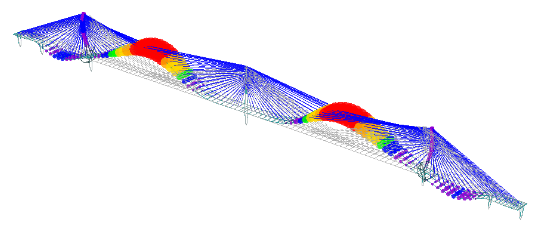
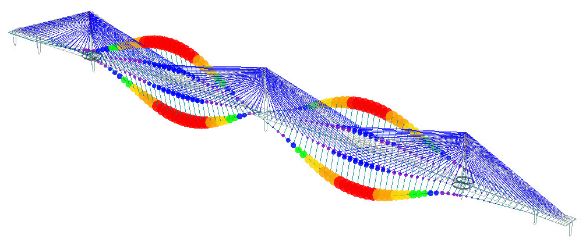
(iv) Effect of structural depth

A structural depth of 4.365 m has been assumed in the above studies for the cable stayed bridge which gives a structural depth of 4.0 m in the approach spans. The depth could be increased by 0.5 m within the current vertical alignment. The effect on the static twist is illustrated below for the orthotropic deck:

Configuration	Orthotropic Deck Shape A	Orthotropic Deck Shape B
Current structural depth	3.6 %	4.5 %
0.5m increase	3.1 %	3.9 %

A 15% reduction in twist results from the increased structural depth. This would also result in increased drag forces on the bridge deck but this is likely to be a small effect compared to the benefit of increased torsional rigidity. For example, the increased structural depth could make the floating connection feasible which would be a major benefit.

(b) Aerodynamic serviceability

First Symmetric Vertical Mode Orthotropic 0.30 Hz Composite 0.27 Hz	
First Torsional Mode Orthotropic 0.47 Hz Composite 0.42 Hz	

Key dynamic modes

The ratio of the modal frequencies is significantly higher than the provisional target ratio of 1.2 required to avoid coupled flutter vibrations.

Historic wind tunnel tests carried out for the Setting Forth and Second Severn studies indicate a reduced torsional galloping (flutter) velocity of at least 4.5 for an aerodynamic box-girder section with 3.0m high wind screens. The reduced velocity is a non-dimensional aerodynamic parameter with the following definition:

$$\frac{U_c}{b \times f_t}$$

Where:

U_C is the critical wind speed for the onset of torsional galloping (m/s)
b is the width of the deck (m)
f_t is the fundamental torsional frequency of the deck (Hz)

This non-dimensional parameter would indicate the following critical wind speeds compared to a target of approximately 60 m/s.

- Orthotropic 81 m/s
- Composite 72 m/s

(i) Contribution of stay cables

Configuration	Orthotropic Deck	Composite Deck
Design stay cable spacing	0.47 Hz	0.42 Hz
Narrow stay cable spacing	0.44 Hz	0.40 Hz

Comparison of torsional frequencies for different configuration

As for the static serviceability, provided that there is torsional restraint at the flanking towers the spacing of the stay cables only has a small effect on the behaviour.

(ii) Benefit of torsional restraint at flanking tower

Configuration	Orthotropic Deck	Composite Deck
Torsional restraint	0.47 Hz	0.42 Hz
Floating connection	0.41 Hz	0.36 Hz

For the composite deck the estimated critical wind speed is reduced to 62 m/s if there is a floating connection at the flanking tower. This is very close to the target of approximately 60 m/s and torsional restraint may well be required to ensure adequate aerodynamic stability. However, this requirement would be confirmed (or otherwise) by wind tunnel tests.

(iii) Effect of deck shape

Configuration	Orthotropic Deck	Composite Deck
Shape A	0.47 Hz	0.42 Hz
Shape B	0.47 Hz	0.40 Hz

As anticipated the effect on the torsional frequency is small. However, the reduced mass and/or modified shape associated with Shape B may result in a lower critical wind speed. This must be determined by wind tunnel testing.

(iv) Effect of structural depth

Configuration	Composite Deck Shape A	Composite Deck Shape B
Current structural depth	0.42 Hz	0.40 Hz
0.5m increase	0.45 Hz	0.43 Hz

As expected the increased structural depth results in higher torsional frequencies for the deck.

(c) Effect of cracking in deck slab

The above results for the composite deck assume transverse prestress to prevent cracking of the deck slab in order to maximise the torsional stiffness of the deck.

Because the deck is centrally supported, the slab is in tension transversely and would crack if it is not prestressed. An initial estimate of the effect of this cracking has been made based on a 50% reduction in the shear stiffness of the slab. The overall effect is a 13% reduction in the torsional stiffness. Based on this assumption the deck would still perform adequately with a cracked slab provided torsional restraint is provided at the flanking towers.

Configuration	Maximum Twist	Torsional Frequency
Uncracked	2.7 %	0.42 Hz
Cracked	3.0 %	0.40 Hz

(d) Conclusion

A single wide box girder with stay cables anchored between the carriageways is a feasible solution for the Mono-Tower.

Two shapes have been considered. Shape A is a conventional streamlined box. Shape B is a box with cantilevers which could offer reduced steel quantities and good visual continuity with the approaches, albeit with slightly poorer torsional performance.

Both orthotropic and composite deck solutions have been considered. It is anticipated that the cost difference between these two deck types is sufficiently small that the most competitive tender prices will be gained by offering both alternatives to the design and build contractor. Therefore adequate serviceability performance of both types must be ensured for any given configuration.

Two different tower forms have been considered, both of which are feasible. The forms considered are either a 9.0 m wide which would allow a slotted solution to be developed or else a minimum width 7.0 m tower.

The potential benefits of the minimum width 7.0 m tower are:

- Reduced cost due to reduced deck area

The potential benefits of the 9.0 m slotted tower are:

- Improved serviceability performance
- Easier connection details between deck and tower due to increased lever arm
- Architectural interest
- Maintenance access

For most configurations torsional restraint is likely to be required at the flanking tower. For the orthotropic box the main issue is twist under eccentric traffic loads. For the composite deck the main issue is aerodynamic stability.

To achieve a floating connection it is likely that box shape A will be required.

As described more fully in Section B.3, an initial sifting exercise was carried out to decide on short listed options to be developed to DMRB Stage 2 Scheme Assessment. The following configuration was selected for the Two Corridor Option:

- Construction Material: Orthotropic or Composite
- Cross Section: Shape A
- Structural Depth: 4.9m
- Restraint at Central Tower: Monolithic
- Restraint at Flanking Towers: Torsional Connection
- Composite Deck Transverse Prestress: Yes
- Tower Type: Narrow 7.0m

B.4.6 Single box girder studies (central cable planes)

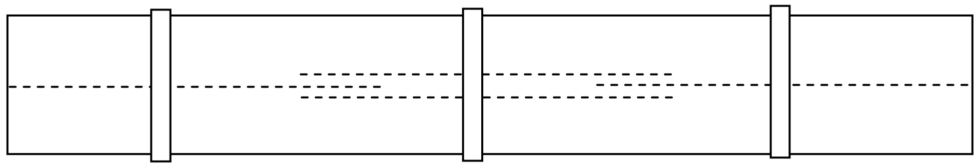
It would in principle also be possible to anchor the stay cables along the centreline of the bridge with a two legged tower as was the arrangement for the Faroe Bridge in Denmark. In this case the serviceability performance would be expected to be similar to the Mono-Tower single deck box girder with narrow stay cable spacing although with a slightly lower critical wind speed due to a narrower deck.

Faroe Bridge, Denmark

Torsional restraint would be required at all towers. Estimated performance parameters are given below assuming Shape A or C with 4.9m structural depth.

Configuration	Orthotropic Deck	Composite Deck
Maximum twist	3.6 %	2.7 %
Torsional frequency	0.47 Hz	0.42 Hz
Inferred critical wind speed	74 m/s	66 m/s

The crossing stays do require that at least one of the cable planes would need to be paired which means that some of the charm achieved by the single plane of cables could potentially be lost.



Schematic plan showing paired central cables

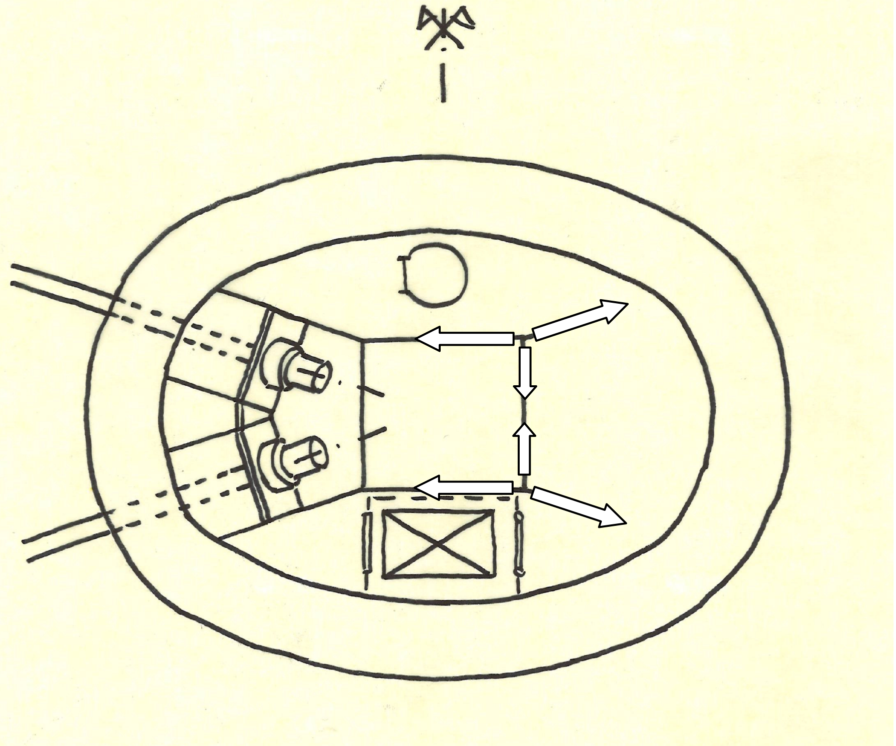
This solution was not carried forward to the Stage 2 Scheme Assessment.

B.4.7 Twin box girder studies (tower form)

For the single deck box girder it was identified that minimising the width of the tower at deck level had a direct impact on deck costs. Although a slim tower at deck level is still important for the twin deck, the marginal cost of a slightly wider tower is lower since the structural zone occupied by the tower is largely a void.

On the other hand the motivation for providing a slot in the tower is also lower since there can be no maintenance corridor along the centre of the bridge to utilise the slot and the architectural benefit is less obvious when the deck itself is already split. However, even without a slot, a slightly wider tower may still be beneficial considering the transverse inclination of the stay cables if they are anchored at the edges.

A study was made of the lower anchorages for Mono-Tower shape M2 (refer to Drawing FRC/C/052/D2M/202 in Appendix D) It was assumed that the shortest two stays could be anchored on corbels on the inside face of the tower but that the third shortest stay would be anchored in the anchor box. A section through the tower at this critical stay location is shown below (assuming the stays anchored on the edge of the deck):



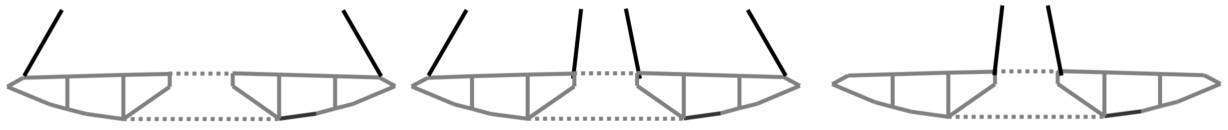
The cross section shows that the anchor box shape for this stay has to be tailored to make sufficient room for the lift. Ordinarily the side web of the anchor box would directly transfer the horizontal load but in this case a crank is introduced into the web such that the longitudinal horizontal force is not transferred via a direct load path. Therefore intermittent cross ties would be required. These would have to be located so that they are not in the way for stay stressing operations. The ties could be made up from vertical plates as indicated in the sketch or – if access to the stays proves to be problematic – from horizontal plates. This arrangement is believed to be achievable because the horizontal force is moderate for this stay. However, a slight easing of the geometry would occur if the 7.0 m dimension at deck level were increased.

B.4.8 Twin box girder studies (stay arrangement)

For the purposes of studying alternative stay arrangements the assumed “base case” articulation is a monolithic connection at the central tower and a floating connection at the flanking towers.

(a) Stay cable arrangements

A number of alternative arrangements are considered with the cables either anchored on the edge of the deck or on the cross girders or both:

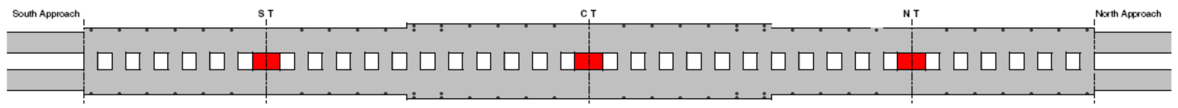


Cables anchored on the outside — *Cable lapping region (applicable to Type B and C)* — *Cables anchored on the inside*

(i) Type A – All stay cables along outer edges

For this arrangement, the torsional support from the cables is maximised by having all the cables anchored on the outside edges of the twin boxes.

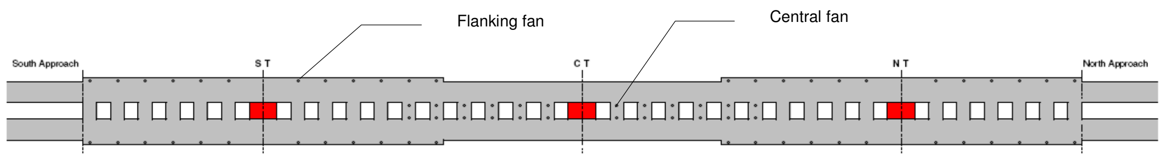
Within the cable overlapping zone of each box girder, two structural zones are required rather than one and the deck width is increased to provide sufficient space. A deck width transition is also required at the movement joints.



Stay Arrangement Type A

(ii) Type B – Central Tower stay cables along inner edges

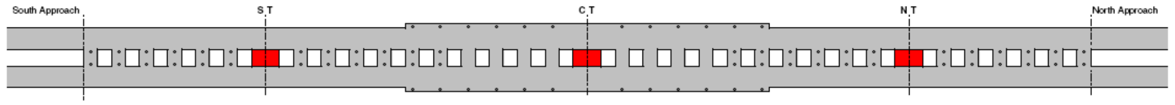
The flanking fan stay cables are anchored on the outside edges of the box girders and the central fan cables on the cross beams. The box girders will require additional width where the cables are on the outside and a deck width transition is required at the movement joints. Where the deck is supported by the cross beams, the torsional stiffness is provided primarily by the box girders. Elsewhere torsional support from the cables can be relied upon.



Stay Arrangement Type B

(iii) Type C – Flanking Tower stay cables along inner edges

The central fan stay cables are anchored on the outside edges of the box girders and the flanking fan cables on the cross beams. Additional deck width is required for the central cables to accommodate the structural zone of the cable anchorages. No box girder width change is required at the movement joints although a change of shape may still be required. Where the deck is supported by the cross beams, the torsional stiffness is provided primarily by the box girders. Elsewhere torsional support from the cables can be relied upon.



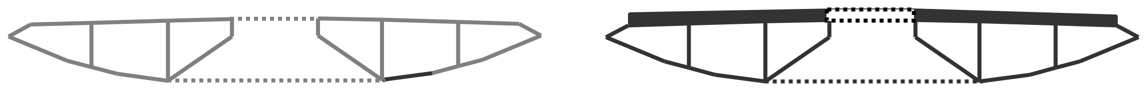
Stay Arrangement Type C

(iv) Type D – All stay cables along inner edges

This arrangement was eliminated through preliminary studies which showed the torsional stiffness to be insufficient.

(b) Options for Structural Forms

The options considered are either an orthotropic steel box girder with steel box girder cross beams or a steel box girder with a composite concrete top slab and steel/concrete composite cross beams.



a) Twin orthotropic box girders with steel box girder cross beams — *b) Twin composite box girders with composite cross beams*

The feasibility studies described herein are based on the orthotropic solution. The concrete composite version would have a similar geometry and as for the single box girder deck it is anticipated that a composite solution would show reduced deflections and twists under traffic loads but also a reduced torsional frequency.

(c) Static Serviceability

The static serviceability has been assessed to determine the maximum deflections and twists that could occur in the bridge deck due to characteristic traffic loads (nominal 1 in 1,000 year return period). The twist is the change in transverse gradient of the bridge at mid span.

Configuration (Orthotropic Deck)	Maximum Deflection (one span only loaded)	Maximum Twist
Type A	3,200 mm	1.3 %
Type B	3,200 mm	2.3 %
Type C	3,350 mm	6.6 %

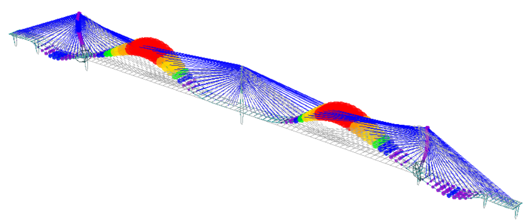
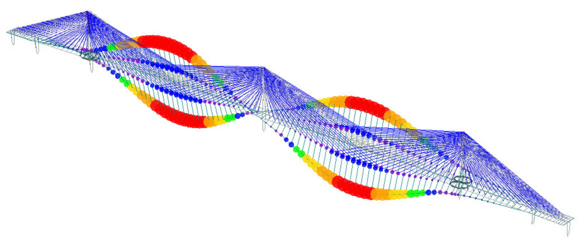
As one would expect the maximum deflection is similar to the single deck option and is largely unaffected by the stay cable configuration. On the other hand, the positioning of the cables has a significant impact on the torsional stiffness of the system and therefore the amount of twist.

For the Type A configuration it is likely that the torsional restraint at the central tower could be released and the deck could be made floating at all towers.

For the Type B configuration the base case articulation should be retained (monolithic at central tower, floating at flanking towers).

The magnitude of the twist for configuration Type C is excessive; however the introduction of torsional restraints at the flanking towers would be likely to reduce the twist to within acceptable limits. As can be seen from Section B.4.3, the provision of a longitudinally free, but torsionally restrained support has practical complexities, and should be avoided if a floating connection can be achieved by an alternative bridge configuration which is in other respects equal. Therefore unless arrangement Type C showed major advantages over Type B (the most directly comparable alternative) it should not be pursued.

(d) Aerodynamic Stability

First Symmetric Vertical Mode Type A 0.28 Hz Type B 0.28 Hz Type C 0.28 Hz	
First Torsional Mode Type A 0.65 Hz Type B 0.50 Hz Type C 0.39 Hz	

Key dynamic modes

The transverse positioning of the cables does not alter the first symmetric vertical mode but does have a significant effect on the first torsional mode.

Some aerodynamic advantages are accrued from the venting of the section so the target frequencies to achieve aerodynamic stability are expected to be lower than for the single deck box girder. By comparison with the single deck results stay cable arrangement Types A and B are likely to be acceptable but Type C is questionable, particularly for a composite deck. However, it has already been established that the Type C arrangement would require torsional restraint at the flanking towers to achieve reasonable twists under eccentric traffic loads. This restraint would also result in a higher torsional frequency and it is likely that the aerodynamic stability would be acceptable.

The ratio of the modal frequencies for all three cable arrangements are higher than the provisional target ratio of 1.2 required to avoid coupled flutter vibrations.

(e) Conclusion

A twin deck box girder with cross girders is a feasible solution for the Mono-Tower.

Three cable arrangements have been considered. Type A has the cables anchored along the outside edge of the deck. For Type B, the cables are anchored along the outside edge for the flanking cable fans and to the cross girders for the central cable fans. For Type C, the cables are anchored to the cross girders for the flanking cable fans and along the outside edge for the central cable fans.

Longitudinally all three behave similarly. Transversely, Type A is expected to perform adequately without torsional connections to the towers whereas Types B and C require torsional connections between deck and tower in the locations where the stay cables are anchored on the cross girders. With torsional restraint being more difficult to arrange at the flanking towers than at the central tower, arrangement Type C appears less favourable.

As described more fully in Section B.3, an initial sifting exercise was carried out to decide on short listed options to be developed to DMRB Stage 2 Scheme Assessment. The following configuration was selected:

- Construction Material: Orthotropic
- Stay Cable Arrangement: Type A (Edges)
- Restraint at Central Tower: Monolithic
- Restraint at Flanking Towers: Floating
- Tower Type: Narrow 7.0m

As described in Section X.X, the narrow tower does result in some geometric congestion at the bottom of the anchor box and future studies could be carried out to determine whether it is beneficial to increase the 7.0m dimension slightly.

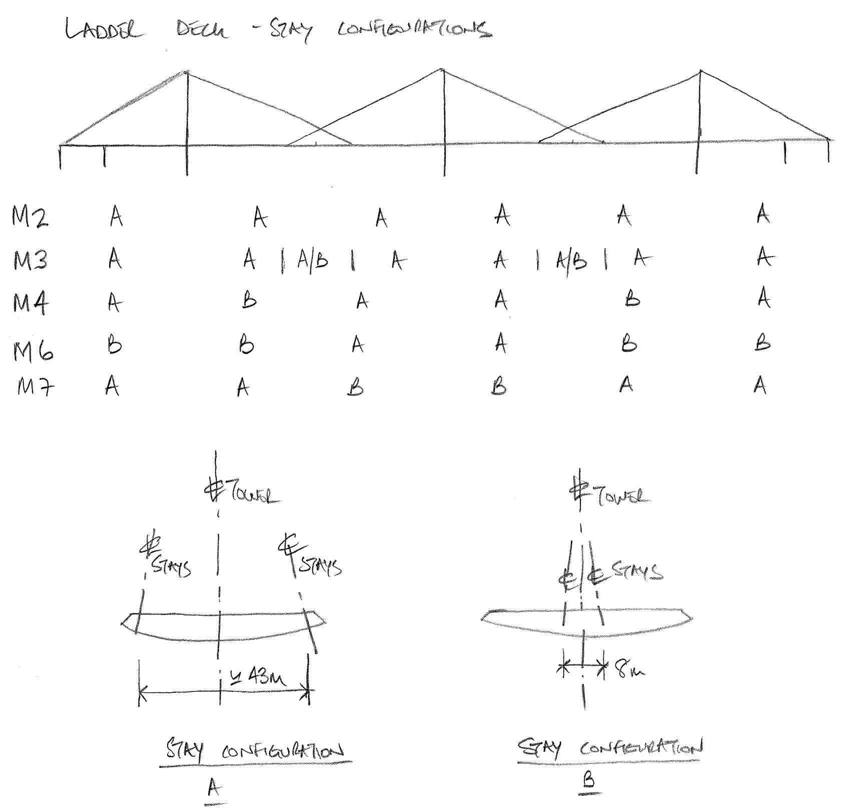
B.4.9 Ladder beam studies (stay arrangement)

A number of different stay configurations have been considered for the Two Corridor Option ladder beam deck. These are illustrated on the sketch below and the accompanying the table below. In summary the configurations studied included arrangements with stays anchored along the outside edge and stays anchored along the central structural corridor.

For all options the tower has been assumed to be 5.5m wide transversely at the top, 9m wide at deck level and 12 m wide at the tower base. As noted in Section B.4.2 above, a slimmer tower appears feasible.

Model Ref.	Stay Layout	Deck Restraint at Flanking Towers
M2	AA AA AA	Lateral
M3	AA (B) AA (B) AA	Lateral
M4	AB AA BA	Lateral
M5	AB AA BA	Lateral & torsional
M6	BB AA BB	Lateral & torsional
M7	AA BB AA	Lateral & torsional

Note for Model M3 only the crossing stays that extend beyond the mid-span point are anchored in the central structural zone. Stays in configuration B were assumed to be 8 m apart whereas stays in configuration A were assumed to be 43.6 m apart.

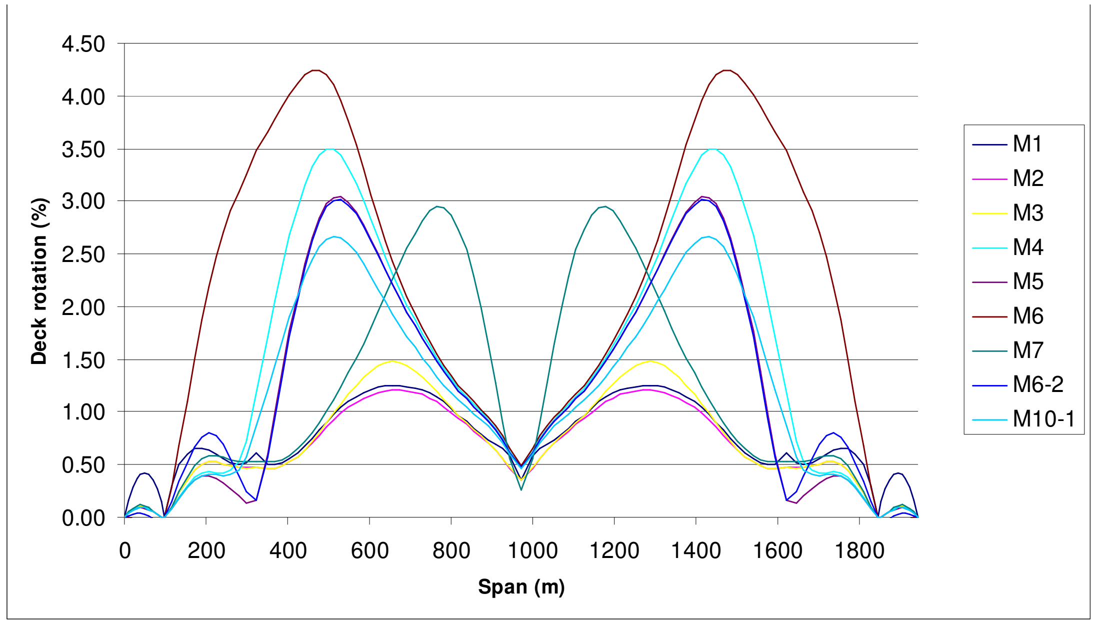


(a) Static Serviceability

Static serviceability deflections for the characteristic (1in 1,000 year return period loading) are given below:

Model Ref.	Maximum Deflection (one span only loaded)	Maximum Twist
M2	3,060 mm	1.2 %
M3		1.5 %
M4		2.8 %
M5		3.0 %
M6		3.0 %
M7		3.0 %

The static torsional behaviour of the bridge deck is illustrated on the plot below which shows the deck twist with one carriageway loaded over the full length of the bridge (



(b) Aerodynamic stability

Aerodynamic stability has been tentatively assessed based on a reduced velocity of 4.5 as described in Section 5.3.1 and considering a deck width of 43 m. This approach leads to the requirement for a fundamental torsional frequency of around 0.31 Hz given a target wind speed of approximately 60m/s. On this basis the deck arrangements with the stays along the outer edges (Model M2) or with only the crossing stays anchored in the central zone (M3) would be the only arrangements which would be acceptable although M5 is marginal.

The predicted wind speed for the onset of flutter depends on the frequency ratio along with a number of other parameters. The predicted flutter speeds based on BD 49/01 for the various stay arrangements considered are shown in the table below.

Model Ref.	First Vertical Mode (f_b)	First Torsional Mode(f_t)	f_t / f_b	Critical Wind Speed	
				Flutter [BD 49/01]	Torsional Galloping
M2	0.195 Hz	0.440 Hz	2.3	84 m/s	85 m/s
M3	0.195 Hz	0.393 Hz	2.0	72 m/s	76 m/s
M5	0.192 Hz	0.303 Hz	1.6	49 m/s	59 m/s
M6	0.196 Hz	0.261 Hz	1.3	35 m/s	50 m/s
M7	0.195 Hz	0.261 Hz	1.3	35 m/s	50 m/s

Note: The effect of increasing the tower height and stay stiffness were investigated but found to offer only a marginal improvement in the dynamic properties. For the purposes of aerodynamic assessment, stay configuration M4 is inferior to M5 and has therefore not been reported.

A more accurate assessment of the deck performance will require the use of flutter derivatives, that in this case, because of the bluff nature of the section would need to be derived using physical model testing.

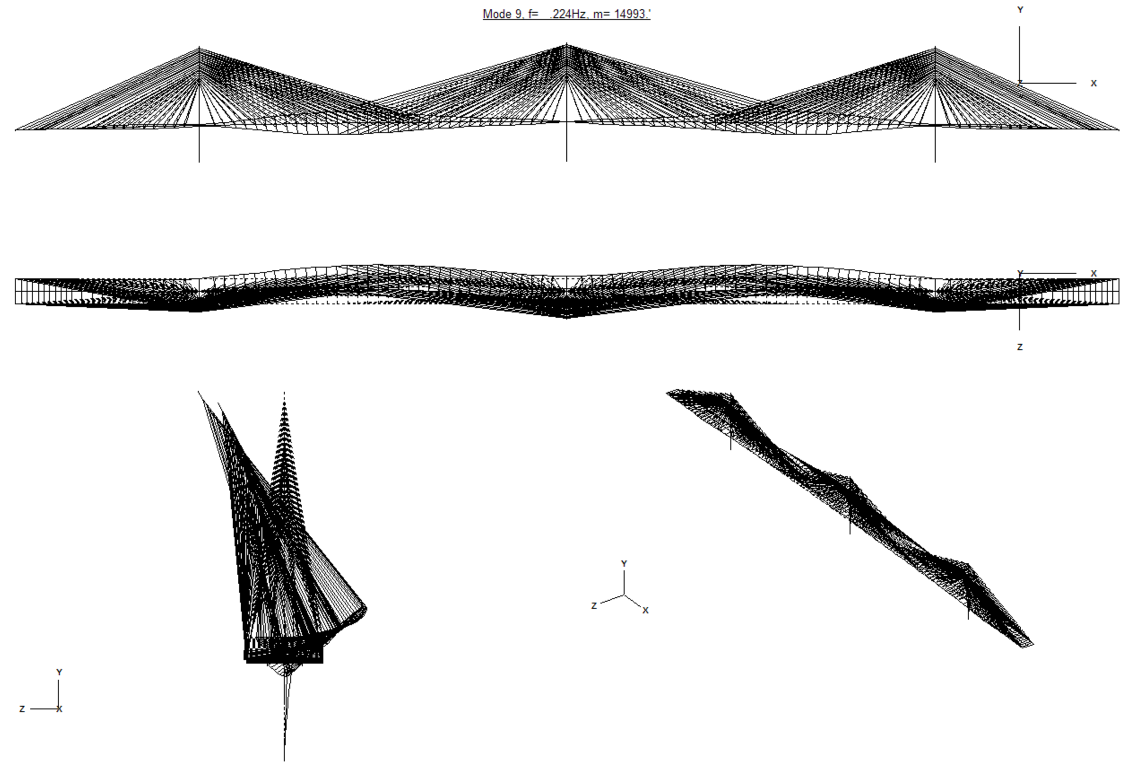
(c) Conclusion

Based on static serviceability considerations, all of the arrangements of stay cables studied are feasible and are likely to result in similar overall construction costs and maintenance costs. Option M2, with all the stays on the outer edges of the deck, is the simplest option. Options M5, M6 & M7 may reduce the overall deck width and may offer aesthetic benefits although these issues are subject to further investigation. The tentative aerodynamic assessment indicates that Option M2 will provide the most favourable performance although it does appear that other options could be proven to be stable if investigated in more detail through initial wind tunnel studies.

As described more fully in Section B.3, an initial sifting exercise was carried out to decide on short listed options to be developed to DMRB Stage 2 Scheme Assessment. Configuration M2 with all the stays on the outer edges of the deck was selected:

B.4.10 Aerodynamic implications of interaction between deck and tower modes

In order to undertake an aerodynamic assessment it is necessary to determine modal properties i.e. frequencies and mode shapes. For the feasibility studies carried out for the ladder beam deck this resulted in some modes that were difficult to readily classify as deck torsion modes as they also include a significant amount of lateral tower motion. For example Mode 9 in Model M5 is shown below which clearly shows that the mode includes deck torsion combined with a significant amount of lateral tower movement:



(a) Assessment to BD 49

Although the ladder deck scheme is beyond the scope of BD 49, the code does provides a conservative way of establishing the aerodynamic performance of the scheme and was used to study the implications of the interaction between modes.

For a plate or box girder ladder deck without a fairing the predicted wind speed for the onset of torsional galloping (U_C) is assessed in BD 49 as:

$$U_C = 3.3B \times f_t$$

Where:

B is the width of the deck (m)
f_t is the fundamental torsional frequency of the deck (Hz)

This approach leads to the requirement for a fundamental torsional frequency of around 0.42 Hz given a target wind speed of approximately 60m/s. On this basis the predicted critical wind speed for Model M2 would be 62 m/s.

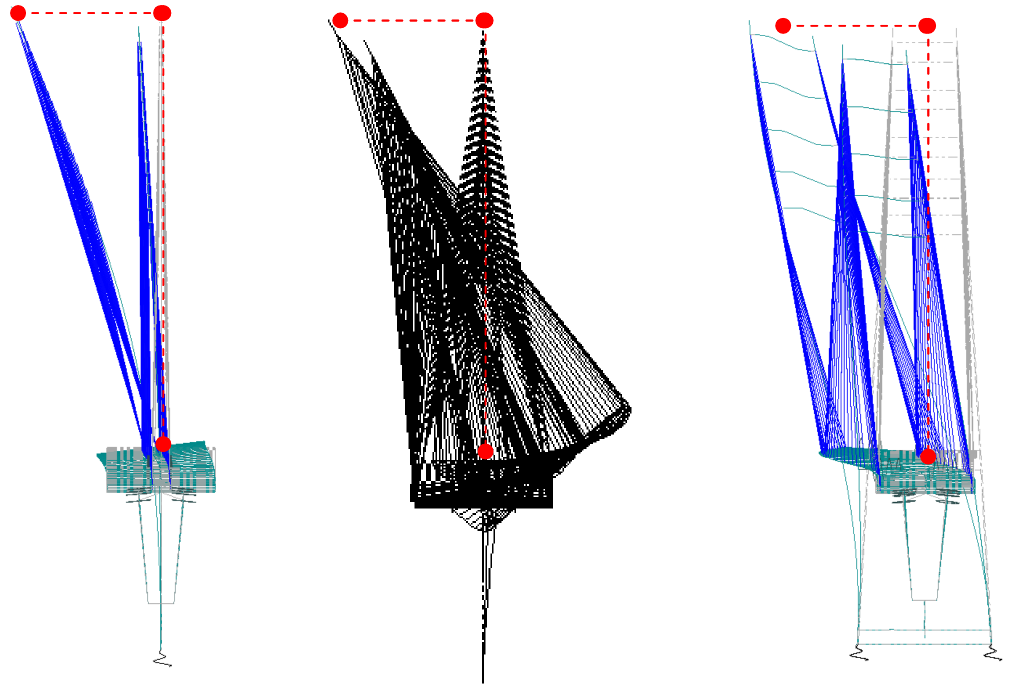
This BD 49 assessment is based on a simple interpretation of the fundamental frequencies and does not consider “complex” modes. However, strict application of BD 49 suggests that the interaction of all modes should be considered including those which exhibit interaction of the deck with the tower. In order to assess complex modes in which both deck and tower movement are observed the modes have been re-normalised based on the maximum deck displacement to derive an equivalent deck mass that can be used in the calculation of flutter speeds using the BD 49 method. This leads to the results shown in the table below for Model M2:

Mode, n	torsion in	1	4	8	15	18	19	20	23	26	27
vertical in	fn (Hz)	0.102	0.152	0.225	0.378	0.441	0.421	0.444	0.506	0.556	0.563
2	0.110		c<0.1	c<0.1	c<0.1	c<0.1	145.3	114.1	c<0.1	233.6	c<0.1
5	0.161			c<0.1	c<0.1	c<0.1	167.4	186.8	c<0.1	200.4	c<0.1
6	0.195			**52.1**	c<0.1	108.8	c<0.1	c<0.1	233.5	c<0.1	170.6
7	0.208			c<0.1	c<0.1	c<0.1	172.5	c<0.1	c<0.1	135.5	c<0.1
10	0.252				129.5	123.7	c<0.1	c<0.1	206.1	c<0.1	144.0
11	0.259				c<0.1	c<0.1	211.4	180.1	c<0.1	c<0.1	c<0.1
12	0.310				111.1	175.9	c<0.1	c<0.1	374.2	c<0.1	135.7
13	0.343				c<0.1	c<0.1	153.6	c<0.1	c<0.1	165.2	c<0.1
14	0.365				c<0.1	c<0.1	c<0.1	c<0.1	216.2	c<0.1	291.0
16	0.398				c<0.1	c<0.1	**45.9**	c<0.1	c<0.1	c<0.1	c<0.1
17	0.421					c<0.1	c<0.1	c<0.1	230.5	c<0.1	214.7
21	0.461					c<0.1		**48.4**	c<0.1	c<0.1	c<0.1
22	0.486								**55.2**	c<0.1	c<0.1
24	0.536									**60.6**	c<0.1
25	0.552									c<0.1	c<0.1

As can be seen this approach suggests that the some of the lower modes may have lower critical wind speeds. This would suggest that wind tunnel testing should be carried out over a range of frequency ratios.

(b) Implications for other schemes

The same phenomenon is not observed for all structural configurations. The equivalent modes are presented side by side for several schemes.



Single box girder Mono-Tower | *Ladder Beam Mono-Tower* | *Single Box Girder H-Shape Tower*

The interaction is an order of magnitude greater for the ladder beam deck. This is consistent with expectations since:

- for the single box-girder mono-tower, anchoring the stays on the deck centre-line decouples the tower and deck
- for the single box girder H-Shape tower, the tower lateral mode shape is an S-curve without significant rotation at the tower top