SECTION A
INTRODUCTION AND OBJECTIVES

The objective of the Phase 1 wind study is to determine the performance of the Golden Gate Bridge in strong winds with a variety of possible suicide deterrent systems added to the existing bridge deck and to evaluate the performance of the bridge with the addition of wind performance enhancement elements. Because the bridge is sensitive to strong winds, the Golden Gate Bridge, Highway and Transportation District specified that any proposed modifications to the bridge should provide for the stability of the bridge in a 100 mph wind, a wind speed with a recurrence interval of approximately 10,000 years.

For new bridges, a typical design criterion is that a flutter instability should not occur for a wind speed with a recurrence interval any less than 10,000 years. For the Golden Gate Bridge, a ten-minute averaged, 10,000 year wind speed at the bridge deck level is 100 mph for winds from the west and approximately 66 mph for winds from the east (Ref 5). See Appendix 1.

The existing railings on the bridge are very solid - with a large horizontal member top and bottom with 4 inch wide H-beam pickets on a spacing of approximately 8 inches. This railing is virtually solid aerodynamically and is one contributing component of the aerodynamic sensitivity of the bridge. Removal of the existing railing increases the critical flutter wind speed by 40%. In the previous study (Ref 2), the wind retrofit system designed for the west side opened up the railing (with new plate pickets parallel to the wind) and added fairings to direct winds smoothly up over the sidewalk and deck. This scheme will increase the critical flutter wind speed to well over 100 mph.

Another scheme that has been proposed (Ref 7) is to add a pair of winglets (one on each side of the bridge) that act as aerodynamic dampers to dampen any torsional (and vertical) disturbance, and not allow it to grow without bound (which is the definition of a flutter instability). The fairing system proposed, and winglet pairs, were considered in this study as reasonable aerodynamic enhancements that can improve the performance of the bridge in strong winds to meet the project criteria.

Three general types of suicide deterrent systems were considered:

Concept 1) Adding to the existing railing to increase its height;
Concept 2) An all new vertical barrier/railing system; and
Concept 3) Nets that cantilever out horizontally.

This wind study resulted in a number of technically feasible suicide deterrent systems from a wind perspective. From an aerodynamic point of view, a technically feasible system must meet the wind speed criteria (in its various forms) for horizontal winds, for winds from -3 degrees, for winds from +3 degrees, and for the suicide deterrent system in combination with a possible moveable traffic barrier in one of seven positions (any possible lane position from one side of the bridge to the other).

In order to meet the specified objective, the wind study was divided into two parts.

Part I - Preliminary Study

In this part of the study the following tasks were performed:

1) Determine base-line aerodynamic characteristics for the existing bridge;

2) Determine the sensitivity of the critical flutter wind speeds to the placement of the moveable traffic barrier in its various positions;

3) Determine the critical flutter wind speeds for the bridge with various generic barrier types (of the three types specified) having different heights and solid ratios (the ratio of the projected area of solid material to the total gross area); and

4) Determine whether or not additional treatment is needed for the proposed suicide deterrent system to meet the specified aerodynamic criteria (critical flutter wind speed greater than 100 mph).

Wind induced motions are produced primarily by the aerodynamic loads on the bridge deck. It is the policy of the West Wind Laboratory to obtain aerodynamic characteristics of the bridge deck using large scale (1:50) model of a section of the bridge deck 267 ft long. At that scale, details in the deck section can be modeled with accuracy.

Aerodynamic characteristics of the bridge deck (static and dynamic) are then used with an analytical model of the turbulent wind field, and an analytical model of the structure, to compute the response of the bridge in a strong wind using a time domain procedure. The wind field is generated using a procedure defined in Ref 3. The time domain analytical procedure is similar to that defined in Ref 4 and is described in greater detail in Appendix 3. If the motions are greater at the end of the numerical simulation than they are at the beginning, then the bridge is unstable (otherwise it is stable). At a design level wind, a static equivalent model response is defined as a mean plus 2.5 standard deviation response. Response statistics are obtained from the numerical simulations for a full-scale period of 10-minutes (See Appendix 3).

A detailed analysis of the existing bridge was performed to determine its baseline critical flutter wind speed. It was noted, in that analysis that 1) the instability observed was a single degree of freedom torsional flutter instability, 2) vertical motions were highly damped, and 3) there was no coupled (vertical and torsional) instability observed amongst any pair of modes of vibration (See Appendix 6). Therefore, it was concluded that in the preliminary studies, critical flutter instabilities could be identified by observing single-degree-of-freedom torsional motion only. A critical flutter wind speed for torsional motion alone was determined as outlined in Appendix 6. This is the maximum critical flutter wind speed possible assuming that the configuration tested is representative of that over the entire bridge.

In this preliminary study, generic barrier types were studied (i.e., barriers of various solid ratios and barriers of various heights). As this iterative process evolved, aerodynamic enhancements were added. Both evolved simultaneously with the current configuration being tested dependent upon the performance of the previous configuration. In this way, 6 configurations (each with multiple traffic barrier options) were identified, out of 72, that met the flutter wind speed criterion. Results of the preliminary study are presented in Section B.

Part II - Detailed Study

In this part of the study, the six aerodynamically independent configurations identified in Part 1 that met the critical flutter wind speed criterion were analyzed. The performance of the Golden Gate Bridge in strong winds, was analyzed with those six configurations, with various moveable traffic barrier locations, at mean angles of incidence of -3, 0, and 3 degrees, for winds from the west, and for winds from the east.

For each possible configuration (for horizontal winds from the west) the maximum possible critical flutter wind speed was identified from torsional motions. For the most critical traffic barrier placement, detailed stability and buffeting analyses were performed for the entire bridge as outlined in Appendix 3. The flutter and buffeting analyses were performed based on measured flutter derivatives, static aerodynamic coefficients and bridge geometric and dynamic modal data. The bridge is modeled using ADINA structural analysis software. A description of the ADINA modeling is provided in Appendix 6.

The aerodynamic enhancements were reduced in spread over the length of the bridge until the stability wind speed criterion was just met. For this configuration, with a reduced spread of the aerodynamic enhancements, a buffeting analysis was performed at the 100 year, design wind speed.

The wind study was based upon aerodynamic coefficients (static and dynamic) on the bridge deck that were obtained experimentally using a large scale (1:50) model of a section of the bridge deck. The section model was based upon the design record drawings from the original construction and from the various modifications to the Bridge (e.g. deck replacement, bottom laterals, public safety railing, etc.)

Results of the detailed study are presented in Section C.

SECTION B
PRELIMINARY STUDIES

Preliminary studies were performed to determine critical flutter wind speeds for the bridge with various suicide deterrent systems. Complete full-bridge analyses were not performed, but simplified analyses were performed, using a large-scale section model (1:50) that allowed torsional motion only (for these studies, vertical motions were constrained). The large-scale section model was used to obtain the aeroelastic flutter derivatives A2 and A3. The stability of the Golden Gate Bridge could then be computed analytically by evaluating the stability of the fundamental torsional mode of vibration (Mode 7 - see Appendix 6). For this bridge, this is a very good approximation to the full-bridge behavior at the critical flutter wind speed, assuming that the configuration being evaluated was representative of that over the entire length of the bridge.

Seventy-two bridge deck configurations were evaluated preliminarily GGB1 through GGB72. Those configurations are described in Tables B.1 and B.2 along with the critical flutter wind speed determined for each. Some results follow:

1) The critical flutter wind speed for the existing Golden Gate Bridge was preliminarily determined and compared to previous studies.

2) The critical flutter wind speed was not sensitive to the existence of, and placement of, a moveable traffic barrier. This is not entirely surprising because a moveable traffic barrier is approximately as high as the existing curb between the roadway and the sidewalk. This insensitivity was identified for the existing configuration as well as a modified configuration (with a critical flutter wind speed in excess of 100 mph).

3) None of the possible suicide deterrent configurations alone (new barrier on top of the existing railing, all new vertical railing and barrier, or horizontal netting scheme) met the critical flutter wind speed criterion of 100 mph. All required some aerodynamic enhancement to meet that criterion.

4) Possible aerodynamic enhancements that were added to meet the criterion were 1) a winglet pair installed above the bridge deck level at the top of a new vertical barrier, 2) winglets and smooth catwalks that behave like winglets below decks in the truss space, and 3) fairings on the west side, over the top chord and along the sidewalk edge. Those fairings had been tested before and are documented in Ref 2.

Only six distinctly different configurations (aerodynamically different) were identified that met the stability criterion (not including all the possible moveable traffic barrier locations). A barrier conforming to Concept 1 or Concept 2 that had vertical, rounded edged glass plates, or vertical rods/cables, or horizontal rods/cables, all with the same solid ratio (ratio of projected area of solid members to total, projected barrier area), are considered to be aerodynamically similar. Those six configurations were advanced to the next study phase as technically feasible solutions. They are identified in Section C.

TABLE B.1 – Critical flutter wind speed (U_{CRIT}) for each bridge deck configuration

CASE	RETRO	*TRAFFIC BARRIER	SUICIDE DETER SYSTEM	U_{CRIT} (mph)	*2-4 DENOTES 2 LANES TO WINDWARD; 4 LANES TO LEE
					*UNLESS OTHERWISE NOTED ALL TESTS AT 0^O
GGB12	WIND	NONE	NONE	>130.69	
GGB13	WIND	0-6	NONE	>127.72	
GGB14	WIND	1-5	NONE	123.48	
GGB15	WIND	2-4	NONE	>130.23	
GGB16	WIND	3-3	NONE	>126.79	
GGB17	WIND	4-2	NONE	>131.17	
GGB18	WIND	5-1	NONE	>130.63	
GGB19	WIND	6-0	NONE	>132.79	
GGB20	FAIRINGS ONLY TO WIND	NONE	SDS2	>129	
GGB21	FAIRINGS ONLY TO WIND	NONE	SDS3	104.7	
GGB22	FAIRINGS TO LEE	NONE	SDS3	77.8	
GGB23	FAIRINGS TO LEE	2-4	SDS3	84.0	

TABLE B.1 (Cont)

CASE	RETRO	*TRAFFIC BARRIER	SUICIDE DETER SYSTEM	U_{CRIT} (mph)
GGB24	FAIRINGS TO LEE	4-2	SDS3	101.6
GGB25	NO	NONE	SDS4	51.5
GGB26	NO	NONE	SDS5	57.1
GGB27	NO	NONE	SDS6	55,6
GGB28	WIND	NONE	SDS6	61.6
GGB29	WIND	NONE	SDS4	77.3
GGB30	NO	NONE	SDS7	>115.9
GGB31	NO	0-6	SDS7	113.9
GGB32	NO	1-5	SDS7	113.6
GGB33	NO	2-4	SDS7	>115.5
GGB34	NO	3-3	SDS7	>115.2
GGB35	NO	4-2	SDS7	>116.2
GGB36	NO	5-1	SDS7	>115.5
GGB37	NO	6-0	SDS7	>115.6
GGB38	NO	NONE	SDS8	55.4
GGB39	NO	NONE	SDS9	57.3
GGB40	NO	NONE	SDS10	73.3
GGB41	NO	NONE	SDS11	52.5
GGB42	NO	NONE	SDS12	77
GGB43	NO	NONE	SDS13	106
GGB44	NO	NONE	SDS14	91
GGB45	NO	NONE	SDS15	>114
GGB46	NO	NONE	SDS16	82
GGB47	NO	NONE	SDS17	93
GGB48	NO	NONE	SDS18	89
GGB49	NO	NONE	SDS19	95
GGB50	NO	NONE	SDS20	101
GGB51	NO	NONE	SDS21	99
GGB52	NO	NONE	SDS22	84
GGB53	NO	NONE	SDS23	99
GGB54	NO	NONE	SDS24	119
GGB55	NO	NONE	SDS25	72
GGB56	NO	NONE	SDS26	57

TABLE B.1 (Cont)

CASE	RETRO	*TRAFFIC BARRIER	SUICIDE DETER SYSTEM	U_{CRIT} (mph)
GGB57	NO	NONE	SDS27	68
GGB58	NO	NONE	SDS28	63
GGB59	NO	NONE	SDS29	105
GGB60	NO	NONE	SDS30	72
GGB61	NO	NONE	SDS31	78
GGB62	NO	NONE	SDS32	77
GGB63	YES	NONE	SDS33	79
GGB64	NO	NONE	SDS34	87
GGB65	NO	NONE	SDS35	108
GGB66	NO	NONE	SDS36	91
GGB67	NO	NONE	SDS37	83.2
GGB68	NO	NONE	SDS38	91.6
GGB69	NO	NONE	SDS39	67.9
GGB70	NO	NONE	SDS40	70.3
GGB71	NO	NONE	SDS41	81.8
GGB72	NO	NONE	SDS42	110.7

TABLE B.2 – Designation and description of the suicide deterrent systems tested

DESIGNATION	SUICIDE DETERRENT SYSTEM
SDS1	10 ft high solid (glass) barriers
SDS2	New full height (to 10 feet) suicide barriers of round members with a solid ratio of 10.4%, both sides
SDS3	New full height (to 10 feet) suicide barriers of round members with a solid ratio of 20.8%, both sides
SDS4	Horizontal netting extending 10 feet out from the edge of the sidewalk, both sides, with a solid ratio of 15.6%
SDS5	The same as SDS4 but with 50 inch wide winglets with the outboard edge 17.92 feet out from the sidewalk
SDS6	Horizontal netting extending 10 feet out from the edge of the sidewalk, both sides, with a solid ratio of 56.9%
SDS7	New, uniform, 10 foot high suicide barriers, with a 50 inch wide winglet at the 10 foot elevation, both sides 20.8% solid
SDS8	Existing railings with suicide barrier on top to 10 feet with a 10.4% solid ratio
SDS9	Existing railings with suicide barrier on top to 10 feet with a 20.8% solid ratio
SDS10	Existing railings, suicide barrier on top to 10 feet with 20.8% solid ratio, with 50 inch wide winglets at the 10 foot level
SDS11	Existing railings with a solid barrier on top up to 10 feet
SDS12	14 foot high barrier/railings both sides with 23% solid ratio
SDS13	Same as SDS12 with 50" winglet and 14' on windward side only
SDS14	Same as SDS12 with 50" winglet at 14' on leeward side only
SDS15	Same as SDS12 with 50" winglets at 14' on both sides
SDS16	SDS12 plus catwalk (50" wide above bottom chord) to windward
SDS17	SDS12 plus catwalks on both sides
SDS18	SDS12 plus enlarged catwalk to lee
SDS19	SDS12 plus enlarged catwalk to wind
SDS20	SDS12 plus catwalks both sides with underside winglet (50" wide at underside of crossbeams) to lee
SDS21	SDS12 plus catwalk and underside winglet to lee only
SDS22	SDS12 plus catwalk and underside winglet to wind only
SDS23	SDS12 plus catwalks both sides and underside winglet to wind

TABLE B.2 (Cont)

DESIGNATION	SUICIDE DETERRENT SYSTEM
SDS24	Existing unmodified railings with 75" wide winglets at 14' both sides, with no new barriers
SDS25	Existing railings with 75" wide catwalk and 75" wide underside winglet to lee only.
SDS26	Existing, plus 10' horizontal net, 21% solid ratio
SDS27	SDS26 with 50" winglet at mid truss height lee side only
SDS28	SDS26 with 50" winglet at edge of net lee side only
SDS29	SDS26 with 75" winglet pair at 14' height
SDS30	New railing and barrier to 14' with 23% solid ratio, tilted inboard 20 degrees
SDS31	SDS30 vertical
SDS32	SDS30 tilted outboard 20 degrees
SDS33	Fairing with new railing and barrier to 14' on west side; existing railing with new barrier above to 14' (23% solid ratio on all new railings and barriers)
SDS34	New railing and barriers to 14' both sides with 23% solid ratio; with 36" winglet at 14' windward side only
SDS35	SDS34 with 36" winglets at 14' both sides
SDS36	SDS34 with 36" winglet at 14' lee side only
SDS37	New barriers 14' high with a 23% solid ratio, and highy curved winglets at 14' that are 36 inches wide (curve on outside with 2.1 feet radius) both sides
SDS38	Same as SDS37 but with 50 inch wide, highly curved winglets
SDS39	Horizontal netting extending 10 feet (16% solid ratio) with new 54 inch high railings with 25% solid ratio
SDS40	SDS39 with sidewalk fairings only to windward
SDS41	SDS39 with a catwalk 50 inch winglet (below deck) to lee
SDS42	SDS39 with a catwalk 50 inch winglet, (below deck) and a second 50 inch winglet on underside of crossbeam, to lee

SECTION C
DETAILED STUDIES

A detailed study was performed to determine the performance of the Golden Gate Bridge with six distinctly different (aerodynamically different) suicide deterrent systems. These configurations were identified from the preliminary studies. The six configurations, plus W1 (alternate), are defined in Figures C.1 through C.7, and are designated W1, W1 (alternate), W2, W3, W4, W5, and W6. The existing bridge configuration is defined as W0.

W0	Existing bridge
W1	12’ tall vertical barrier with solid ratio of 23% and under deck winglets and/or catwalk. An alternate to W1 is the use of wind fairings in lieu of winglets
W2	12’ tall vertical barrier with solid ratio of 23% and winglets mounted over the new barrier
W3	A new vertical barrier mounted over the existing railing with a maximum solid ratio of 12% and with winglets mounted over the new barrier
W4	Similar to W1 except a new barrier height of 10’ instead of 12’
W5	Similar to W2 except with a new barrier height of approximately 10’ and with a winglet mounted at 10’-6”
W6	A horizontally projecting net. Net projection of 10’ with a maximum solid ratio of 16%. Modify existing railing to have a maximum solid ratio of 23%. Below deck winglets and catwalk required

The objectives of this portion of the study were the following:

1) determine the maximum possible critical flutter wind speeds for each configuration, with and without moveable traffic barriers in any of 7 possible locations, for winds with vertical angles of incidence of -3, 0, and 3 degrees;

2) determine the minimum length (spread) of aerodynamic enhancements (fairings or winglets) required for each configuration to just meet the critical flutter wind speed threshold of 100 mph; and

3) for each configuration with minimal spread aerodynamic enhancements, determine the buffeting response of the bridge to a turbulent wind field with a mean hourly wind speed of 76 mph.

It is instructive first to determine the performance, precisely, of the existing bridge. The dynamic response characteristics of the bridge, and its inertial properties, are presented in Appendix 6. A detailed stability analysis was performed as described in Appendix 3. Results of that stability analysis, including 10 modes of vibration simultaneously, are presented in Table C.1. All modes of vibration were given an initial unit disturbance. If the last-to-first ratio of modal responses (after 5 minutes of exposure to the specified wind speed) is greater than 1.00, then that mode of vibration (and the entire bridge) is unstable.

Note that the vertical modes of vibration (Modes 2, 4, 5, 6, and 9) are highly damped at all wind speeds. Shown in Table C.2 are the frequencies at which each mode of vibration is vibrating. Note that for all strong wind speeds, almost all modes are coupling aerodynamically (by definition of a normal mode of vibration, they are decoupled mechanically) to the first asymmetric torsional mode (Mode 7), or the first symmetric torsional mode (Mode 8). This is identified because the modal frequencies are all matched to the torsional modes. These are not coupled instabilities, but are responses of those non-torsional modes from the coupling aeroelastic flutter derivatives, notably A1 and H3, that are driving the vertical response. The torsional motions are driving the vertical modes of vibration aerodynamically. Table C.3 shows the mean magnitude of the modal response at the end of the simulation. All numbers are small relative to unity, so static divergence did not occur (except the Mode 1 response which is just an expected, mean sway).

This analysis of the existing bridge is instructive for the following reasons:

1) The only possible instability is a torsional instability;

2) Vertical motions are highly damped;

3) No coupled instability occurs (although other modes are driven by the torsional motions); and

4) The critical flutter wind speed obtained in this study is very close to that obtained for the existing bridge considering torsional motion alone for Case GGB1 in the preliminary studies.

These conclusions are used to guide the detailed analyses of the bridge with the suicide deterrent systems that have been advanced to this phase.

For the options considered, to do detailed stability and buffeting analyses, a full set of aeroelastic flutter derivatives, and static aerodynamic coefficients are required. That was not done explicitly, but done implicitly using the conclusions from the analyses of the existing bridge. A torsional aeroelastic instability is governed by the aeroelastic flutter derivatives A2 and A3. Those were measured explicitly for each option. Since the vertical motions of the bridge were highly damped, the precise measurement of the H1 and H4 aeroelastic terms was not required. It is a fact, however, that at high wind speeds (and large values of *U/nB* where *U* is the mean wind speed, *n* is the frequency of vibration, and *B* is the bridge chord - 27.432m) the aeroelastic flutter derivatives approach asymptotically values well defined from the static coefficients alone. For

$$K = 2\pi n \frac{B}{U}$$

H1 approaches $-\left(\frac{1}{K}\right)\frac{dC_L}{d\alpha}$

H3 approaches $\left(\frac{1}{K^2}\right)\frac{dC_L}{d\alpha}$

A1 approaches $-\left(\frac{1}{K}\right)\frac{dC_M}{d\alpha}$

for all values of *U/nB* (Ref 1). The static coefficients (C_D, C_L, C_M) for all options were measured and are presented in Appendix 7. The rate of change of C_L and C_M with angle of incidence, α, could then be computed. In this way H1, H3, and A1 were computed from the static aerodynamic coefficients.

The remaining aeroelastic flutter derivatives (H2, H4, and A4) play a very minor role in computing the aeroelastic stability of this bridge because no coupled flutter is expected. The values for the existing bridge were used as being representative of the various options.

Torsional flutter instabilities were computed first for the various options from torsional motions alone assuming that the specified option was representative of the crossection of the bridge for its full length. Critical flutter wind speeds were computed as described in Appendix 6 using the single torsional mode of vibration, Mode 7. For each option measurements were made for the following cases:

1) Angle of incidence equal to 0 degrees, traffic barriers in the 0, 1, 2, 3, 4, 5, 6, and 7 positions (0 - up against the windward curb; 6 - up against the leeward curb; 7 - no traffic barrier at all);

2) Angle of incidence equal to -3 degrees (downward angle), traffic barriers in the 1, 3, 5, and 7 positions; and

3) Angle of incidence equal to 3 degrees, traffic barriers in the 1,3,5, and 7 positions.

For the non-zero angles of incidence, for the traffic barrier positions not tested specifically, critical flutter wind speeds were interpolated from those wind speeds that were measured.

For the options W1, W2, W3, W5, and W6 the values of A2 andA3 were obtained and a critical flutter wind speed was computed. In those tables the following designations are used

Wabcd

where

a option number;
b wind angle (1 = -3 degrees, 2 = 0 degrees, 3 = +3 degrees);
c traffic barrier position;
d wind direction (1 - west wind; 2 - east wind).

A summary of the critical flutter wind speeds obtained is presented in Tables C.4 through C.8. Option W4 is similar to W1, but less critical, and so was not tested specifically. Option W1 (alternate) is not critical compared to W1, and was not tested over the full range relative to W1. The values of A2 and A3 were measured specifically for W1 (alternate) at a zero angle of incidence, without traffic barriers, for west winds. Those result are presented in Appendix 6 as W1271A.

It should be noted that for all cases, for zero angles of incidence, the critical flutter wind speeds are all equal to or greater than 100 mph, except W1201 which is 99.7 mph. For many of the non-zero angles of incidence this criterion is not met. If, under an extreme wind, the bridge deforms excessively in torsion, this criterion should be met at that particularly non-zero angle of incidence. This does not occur for the Golden Gate Bridge in any of its options (see the mean response of Modes 7 and 8 in the buffeting analyses). Steady, strong, mean winds at non-zero angles of incidence would be extremely rare (except for winds on the north side span, from the west, over the Marin Headlands). It is therefore typical in the profession to reduce the critical flutter wind speed threshold (the criterion) as a function of vertical angle of incidence. Typical reduction scale factors are 0.8 at angles of incidence of plus or minus 2.5 degrees; and 0.5, at angles of incidence of plus or minus 5.0 degrees. Linearly interpolating, this converts to a reduction scale factor of 0.733 at plus or minus 3 degrees. That would define a critical flutter wind speed threshold of 73.3 mph at those non-zero angles of incidence. This reduction in critical flutter wind speed threshold has been accepted for many bridge designs throughout the world, specifically the Lantau Crossing bridges in Hong Kong, and the new Cooper River Bridge in Charleston, South Carolina. This reduction schedule has been in use since the 1950's. All of the non-zero results for all of the options considered in this study do meet this criterion.

For several options, for horizontal winds from the west, the critical flutter wind speed greatly exceeded the criterion of 100 mph. For those cases, the aerodynamic enhancements are not required to extend for the full length of the bridge. Mode 7 torsional motions on the sidespans are minimal. Aerodynamic enhancements (winglets and fairings) contribute nothing to the stabilization of Mode 7 if placed on the sidespans. Mode 8 torsional motions are small on the sidespans. The effectiveness of the aerodynamic enhancements on the sidespans to Mode 8 is real, but minor.

Detailed stability analyses were therefore performed for each optional crossection (W1 - W6) with the aerodynamic enhancements (winglets or fairings) distributed over differing portions of the bridge. Aerodynamic enhancements are most effective if placed where torsional modal displacements are greatest (the one-quarter span lengths at the quarter points of the main span for Mode 7, and the middle half-span of the main span for Mode 8). Therefore, the possible distributions of aerodynamic enhancements considered are those shown on Figures C.8, C.9 and C.10. For the regions where there are no aerodynamic enhancements proposed, aeroelastic flutter derivatives for those cases shown in the following table were used.

OPTION	CASE WITHOUT AERODYNAMIC ENHANCEMENTS
W1	GGB42
W1 (alt)	GGB42
W2	GGB42
W3	GGB1
W5	GGB42
W6	GGB69

The flutter derivatives were used for the various options (W1 - W6) for zero angle of incidence, for a barrier placed that produced the lowest critical flutter wind speed. Those specific cases used were as follows:

OPTION	CRITICAL CASE USED
W1	W1201
W1 (alt)	W1271A
W2	W2201
W3	W3231
W5	W5201
W6	W6201

It should be noted that many of the critical cases had the barrier on the windward curb. Extreme winds come from the west, so stow the traffic barrier on the east curb, not the west. For these detailed analyses, winds were horizontal and from the west. For the cases without the aerodynamic enhancements, no barriers were in place. These are areas of little aerodynamic importance (hence no enhancements are needed there), and critical flutter wind speeds are generally insensitive to barrier placement, so only minor second order errors are expected with the use of these preliminary study values, in these non-critical locations.

The results of these analyses indicated that aerodynamic enhancements are required, for the various options, only over those portions identified in Figures C.11 through C.13. For each of those cases, results of the stability analyses are presented in Tables C.9 through C.14. Note that for case W1201 (Option W1 with a traffic barrier at position 0) the critical flutter wind speed is only 98 mph. For all other traffic barrier placements, or no traffic barrier, the critical flutter wind sped exceeds 100 mph, i.e., do not store the traffic barrier to the west.

For all of these studies, the extreme wind was assumed to come from the west. From Ref 5 (see Appendix 1) the percentage of time that 100 year wind speeds (or greater) come from the east (at the San Francisco International Airport, and similarly at the Golden Gate Bridge) are three orders of magnitude lower than the percentage of time those winds come from the south or west. Probabilities are proportional to these percentages, and return periods are proportional to the inverse of those probabilities. Therefore a 100 year, one hour averaged wind speed of 76 mph from the west corresponds to 100,000 year, one hour averaged wind speed from the east. The options W1, W1 (alternate), and W6 are unsymmetric. The preliminary cases that correspond to the W1 - W6 options for wind from the east, and their critical flutter wind speeds are as follows (all cases without traffic barriers):

OPTION FOR WEST WIND	CASE FOR EAST WIND	U_{CRIT} (mph) FOR EAST WIND
W1	GGB53	99
W1 (alt)	GGB42	77
W2	-	>118
W3	-	119
W5	-	>118
W6	GGB41	82

For all cases the critical flutter wind speeds for each winds exceed the 100,000 year wind speed from the east of 76 mph.

For Cases 0W1201, 4W2201, 2W3231, 4W5201, 4W6201, and 4W1271A (where the first number indicates the lateral spread of aerodynamic enhancements required to meet the stability criterion - see Figures C.8, C.9, and C.10) buffeting analyses were performed (using the numerical simulation procedure defined in Appendix 3). With the peak nodal displacements, member actions and stresses throughout the bridge for each mode of vibration can then be determined. A stress at any point can then be computed as the square-root-of-the-sum-of-the-square (SRSS) combination of those modal stresses (or some other reasonable combination procedure).

It should be noted that a buffeting analysis, at the 100 year design level wind speed, could not be computed (at 34 m/s) for the existing bridge. However, buffeting analyses can be compared to the existing state through their static aerodynamic coefficients. Static aerodynamic coefficients for various options are shown below:

CASE	C_D	$dC_L / d\alpha$	$dC_M / d\alpha$
W0	.357	3.203	-.002
W1	.371	2.989	.377

W2	.371	2.964	.346
W3	.394	2.627	.404
W6	.356	2.455	.273

The drag coefficients with the suicide deterrent and aerodynamic enhancement systems are generally higher than the drag coefficient for the existing case, by as much as 10% for W3, but generally by as much as 4% for options W1, W2, and W6. The vertical buffeting response is proportional to the slope of the lift curve ($\frac{dC_L}{d\alpha}$). In all cases, with the suicide deterrent and aerodynamic systems, the slope of the lift curve is less than what it is for the existing state. In all cases too, the slope of the moment coefficient is significantly greater than it is for the existing case, and torsional motions are proportional to the slope of the moment coefficient. However, the absolute values (typically are less than 0.4) are small compared to the maximum possible of 1.5708 for an airfoil.

TABLE C.1

EXISTING CONDITION 4/2/7

RATIO OF FINAL MODAL STANDARD DEVIATION RESPONSES TO INITIAL MODAL STANDARD DEVIATION RESPONSES

LENGTH OF RECORD (SEC) 300

WWL	DMJM	U(M/S) - TEN MINUTE AVERAGED WIND SPEED AT DECK						
MODE	MODE	20.0	22.0	24.0	26.0	28.0	30.0	32.0
1	1	0.234	0.213	0.193	0.175	0.159	0.145	0.131
2	2	0.024	0.017	0.016	0.034	0.097	0.255	0.717
3	3	0.104	0.093	0.083	0.074	0.066	0.059	0.056
4	4	0.010	0.013	0.023	0.046	0.093	0.214	0.574
5	5	0.062	0.052	0.039	0.043	0.091	0.214	0.635
6	6	0.008	0.006	0.009	0.017	0.038	0.088	0.234
7	7	0.135	0.196	0.307	0.557	1.093	2.341	5.515
8	8	0.086	0.115	0.153	0.216	0.352	0.645	1.310
9	9	0.011	0.008	0.004	0.005	0.012	0.028	0.093
10	10	0.043	0.044	0.058	0.065	0.103	0.197	0.461

TABLE C.2

EXISTING CONDITION 4/2/7

FINAL MODAL FREQUENCIES

LENGTH OF RECORD (SEC) 300

WWL MODE	DMJM MODE	U(M/S) - TEN MINUTE AVERAGED WIND SPEED AT DECK 20.0	22.0	24.0	26.0	28.0	30.0	32.0
1	1	0.050	0.050	0.050	0.050	0.050	0.050	0.050
2	2	0.087	0.140	0.177	0.177	0.180	0.180	0.180
3	3	0.110	0.110	0.110	0.110	0.110	0.110	0.109
4	4	0.129	0.193	0.192	0.192	0.192	0.192	0.191
5	5	0.134	0.133	0.131	0.188	0.183	0.181	0.180
6	6	0.159	0.206	0.198	0.193	0.194	0.194	0.194
7	7	0.182	0.182	0.181	0.181	0.180	0.180	0.180
8	8	0.195	0.194	0.195	0.194	0.194	0.194	0.194
9	9	0.198	0.201	0.213	0.180	0.180	0.180	0.182
10	10	0.203	0.202	0.201	0.192	0.191	0.192	0.193

TABLE C.3

EXISTING CONDITION 4/2/7

CHECK FOR STATIC DIVERGENCE
FINAL AVERAGE MODAL RESPONSES

LENGTH OF RECORD (SEC) 300

WWL MODE	DMJM MODE	U(M/S) - TEN MINUTE AVERAGED WIND SPEED AT DECK 20.0	22.0	24.0	26.0	28.0	30.0	32.0
1	1	-0.940	-1.140	-1.359	-1.597	-1.854	-2.130	-2.425
2	2	-0.004	-0.003	-0.002	0.000	0.003	0.040	0.126
3	3	-0.007	-0.006	-0.006	-0.005	-0.004	-0.003	-0.001
4	4	-0.025	-0.029	-0.035	-0.040	-0.047	-0.057	-0.075
5	5	-0.001	-0.000	-0.000	-0.000	-0.000	-0.013	-0.042
6	6	-0.009	-0.011	-0.013	-0.015	-0.018	-0.021	-0.026
7	7	0.008	0.012	0.014	0.016	0.034	-0.069	-0.241
8	8	-0.022	-0.027	-0.030	-0.042	-0.053	-0.073	-0.107
9	9	0.000	0.000	0.000	0.000	0.000	-0.001	-0.005
10	10	0.018	0.022	0.028	0.030	0.034	0.035	0.033

TABLE C.4
CRITICAL FLUTTER WIND SPEED (mph)
CASE W1

ANGLE OF INCIDENCE (DEGREES)	TRAFFIC BARRIER	U_{CRIT} (mph)
0	NONE	105.4
0	0	99.7
0	1	107.1
0	2	112.3
0	3	>118.0
0	4	>119.0
0	5	118.4
0	6	109.0
-3	NONE	107.7
-3	0	103.9
-3	1	103.9
-3	2	110.8
-3	3	>117.6
-3	4	116.0
-3	5	114.4
-3	6	107.7
3	NONE	85.6
3	0	85.6
3	1	92.4
3	2	96.5
3	3	100.6
3	4	97.4
3	5	94.1
3	6	85.6

TABLE C.5
CRITICAL FLUTTER WIND SPEED (mph)
CASE W2

ANGLE OF INCIDENCE (DEGREES)	TRAFFIC BARRIER	U_{CRIT} (mph)
0	NONE	>117.8
0	0	116.8
0	1	>117.9
0	2	>119.2
0	3	>119.6
0	4	>119.3
0	5	>119.6
0	6	116.9
-3	NONE	92.0
-3	0	92.0
-3	1	91.6
-3	2	91.3
-3	3	91.1
-3	4	95.6
-3	5	100.2
-3	6	92.0
3	NONE	>120.6
3	0	>120.6
3	1	>117.6
3	2	>117.6
3	3	>118.8
3	4	>118.8
3	5	>121.2
3	6	>120.6

TABLE C.6
CRITICAL FLUTTER WIND SPEED (mph)
CASE W3

ANGLE OF INCIDENCE (DEGREES)	TRAFFIC BARRIER	U_{CRIT} (mph)
0	NONE	118.8
0	0	121.5
0	1	119.1
0	2	118.3
0	3	113.9
0	4	116.3
0	5	118.5
0	6	110.1
-3	NONE	83.9
-3	0	83.9
-3	1	80.3
-3	2	87.2
-3	3	94.5
-3	4	90.3
-3	5	86.1
-3	6	83.9
3	NONE	91.5
3	0	91.5
3	1	89.9
3	2	88.0
3	3	86.0
3	4	86.2
3	5	86.3
3	6	91.5

TABLE C.7
CRITICAL FLUTTER WIND SPEED (mph)
CASE W5

ANGLE OF INCIDENCE (DEGREES)	TRAFFIC BARRIER	U_{CRIT} (mph)
0	NONE	112.3
0	0	100.3
0	1	116.2
0	2	>120.9
0	3	>116.9
0	4	>119.2
0	5	>121.2
0	6	>119.3
-3	NONE	90.7
-3	0	90.7
-3	1	83.1
-3	2	88.0
-3	3	92.9
-3	4	92.6
-3	5	92.3
-3	6	90.7
3	NONE	102.7
3	0	102.7
3	1	>118.9
3	2	>118.5
3	3	>118.5
3	4	116.15
3	5	113.8
3	6	102.7

TABLE C.8
CRITICAL FLUTTER WIND SPEED (mph)
CASE W6

ANGLE OF INCIDENCE (DEGREES)	TRAFFIC BARRIER	U_{CRIT} (mph)
0	NONE	>113.5
0	0	104.8
0	1	105.6
0	2	>114.2
0	3	>115.5
0	4	>112.9
0	5	>112.7
0	6	>119.3
-3	NONE	104.0
-3	0	104.0
-3	1	95.3
-3	2	98.2
-3	3	101.0
-3	4	105.0
-3	5	109.0
-3	6	104.0
3	NONE	>114.5
3	0	>114.5
3	1	114.2
3	2	109.7
3	3	>109.7
3	4	109.8
3	5	109.9
3	6	>114.5

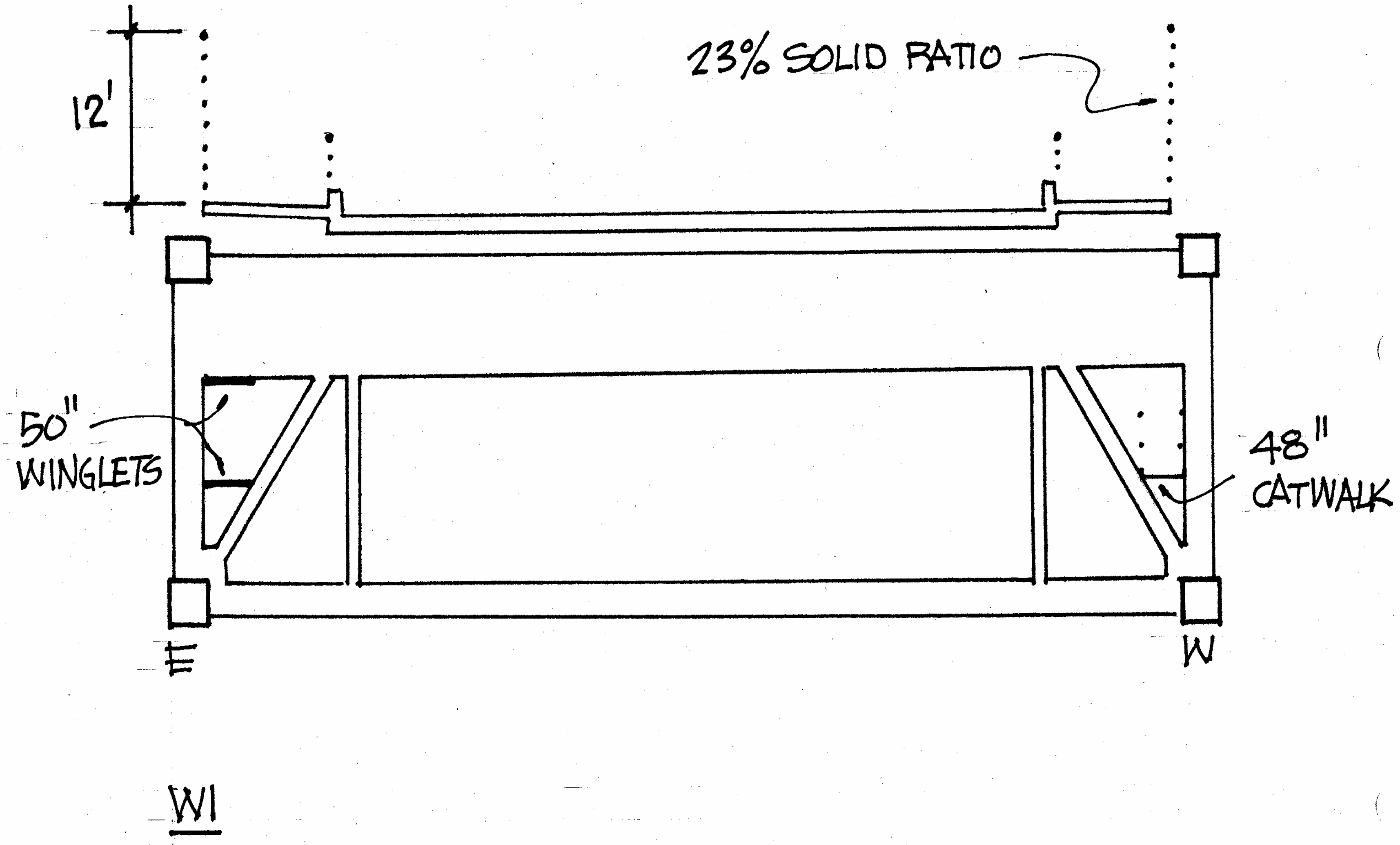


FIGURE C.1 - 12’ tall vertical barrier with solid ratio of 23% and under deck winglets and/or catwalk

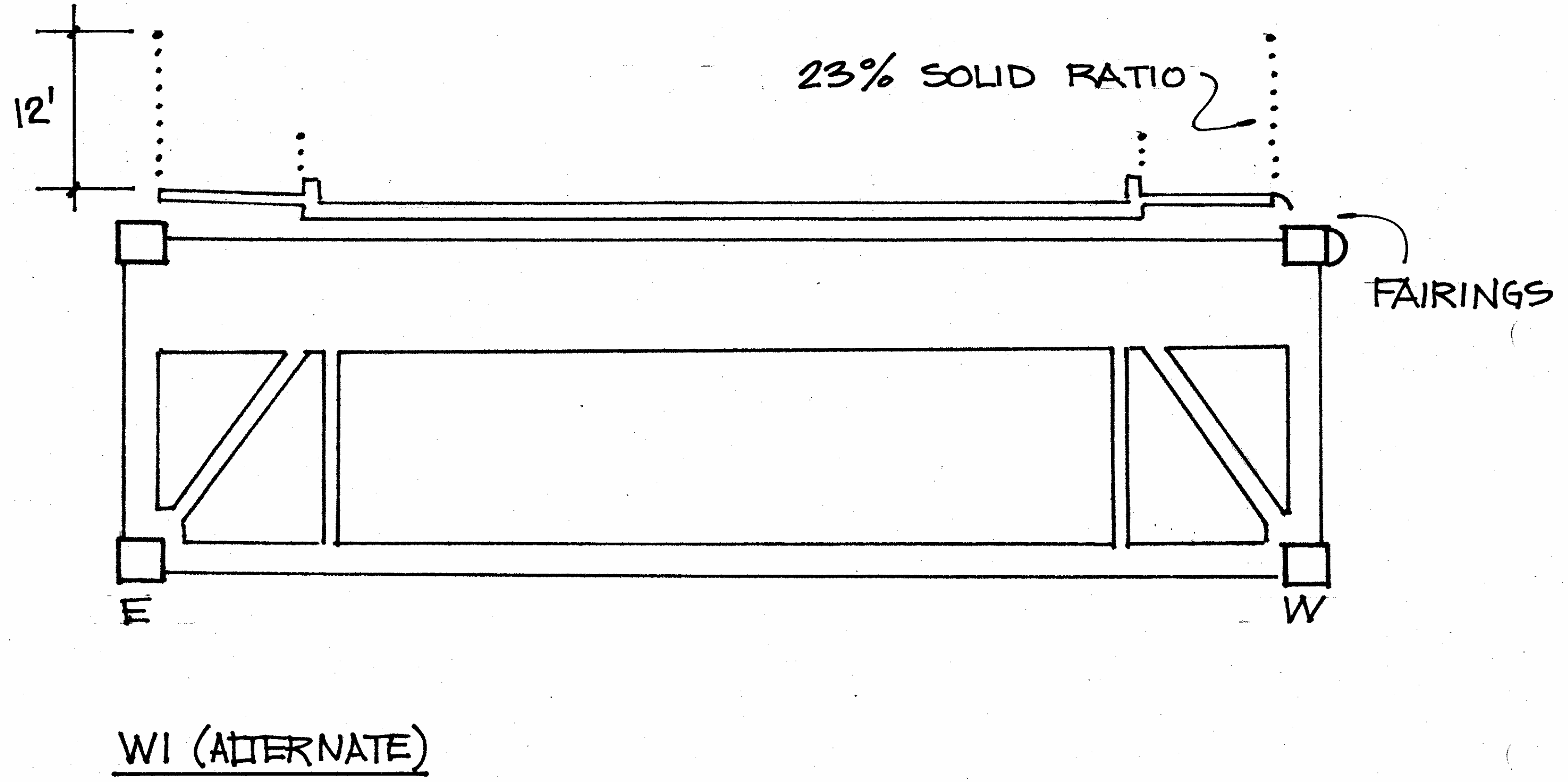


FIGURE C.2 - 12’ tall vertical barrier with solid ratio of 23% and use of wind fairings in lieu of winglets

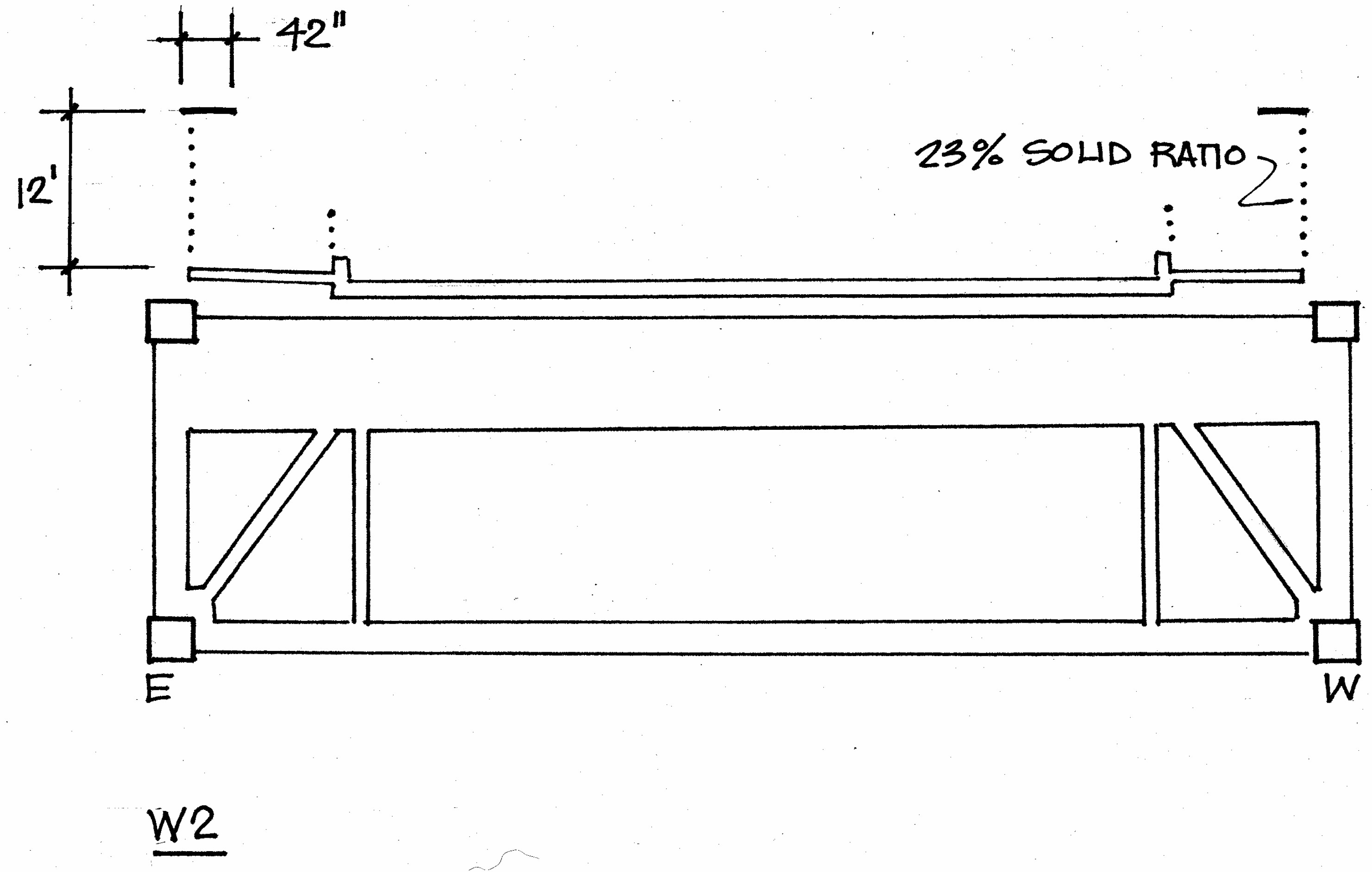


FIGURE C.3 - 12’ tall vertical barrier with solid ratio of 23% and winglets mounted over the new barrier

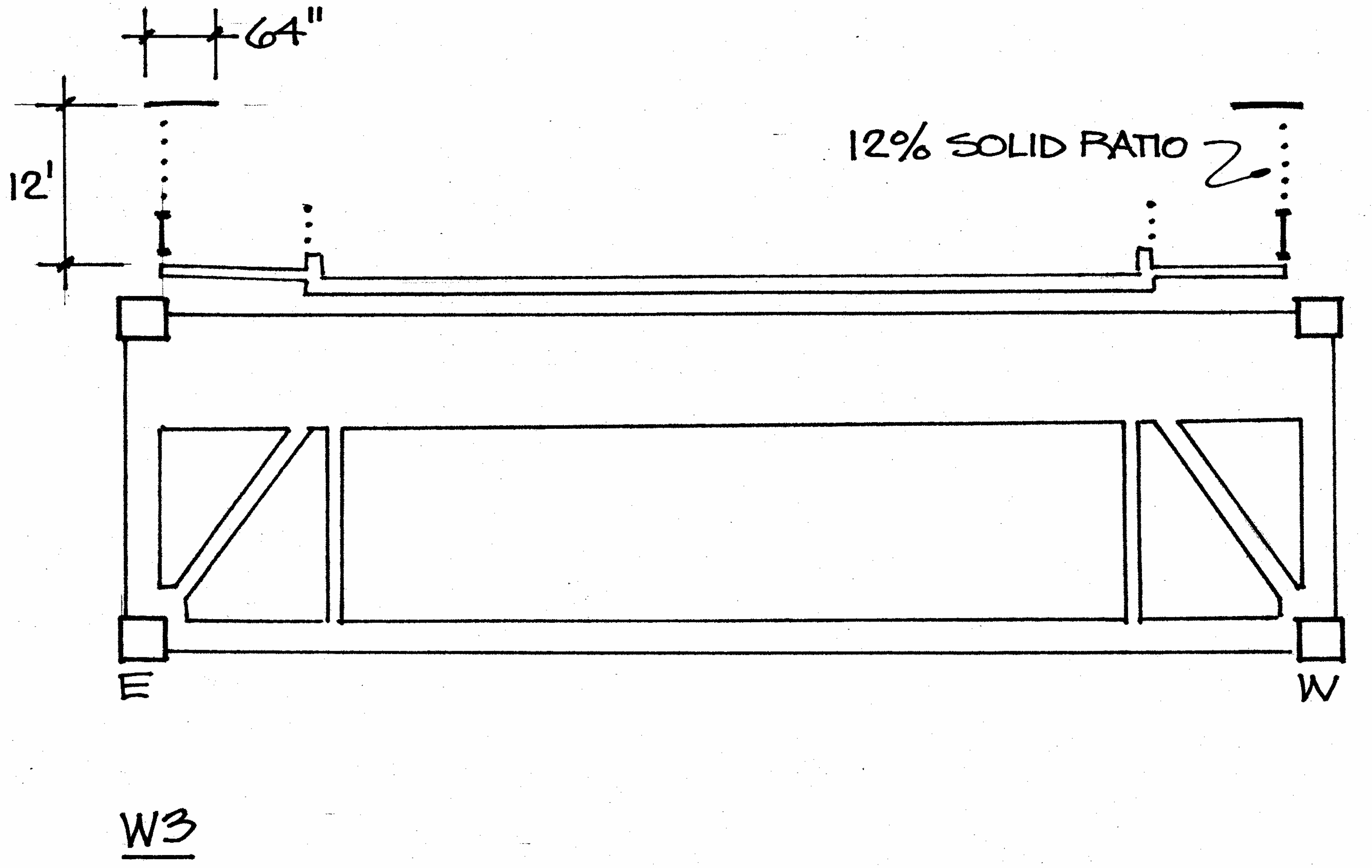


FIGURE C.4 - A new vertical barrier mounted over the existing railing with a maximum solid ratio of 12% and with winglets mounted over the new barrier

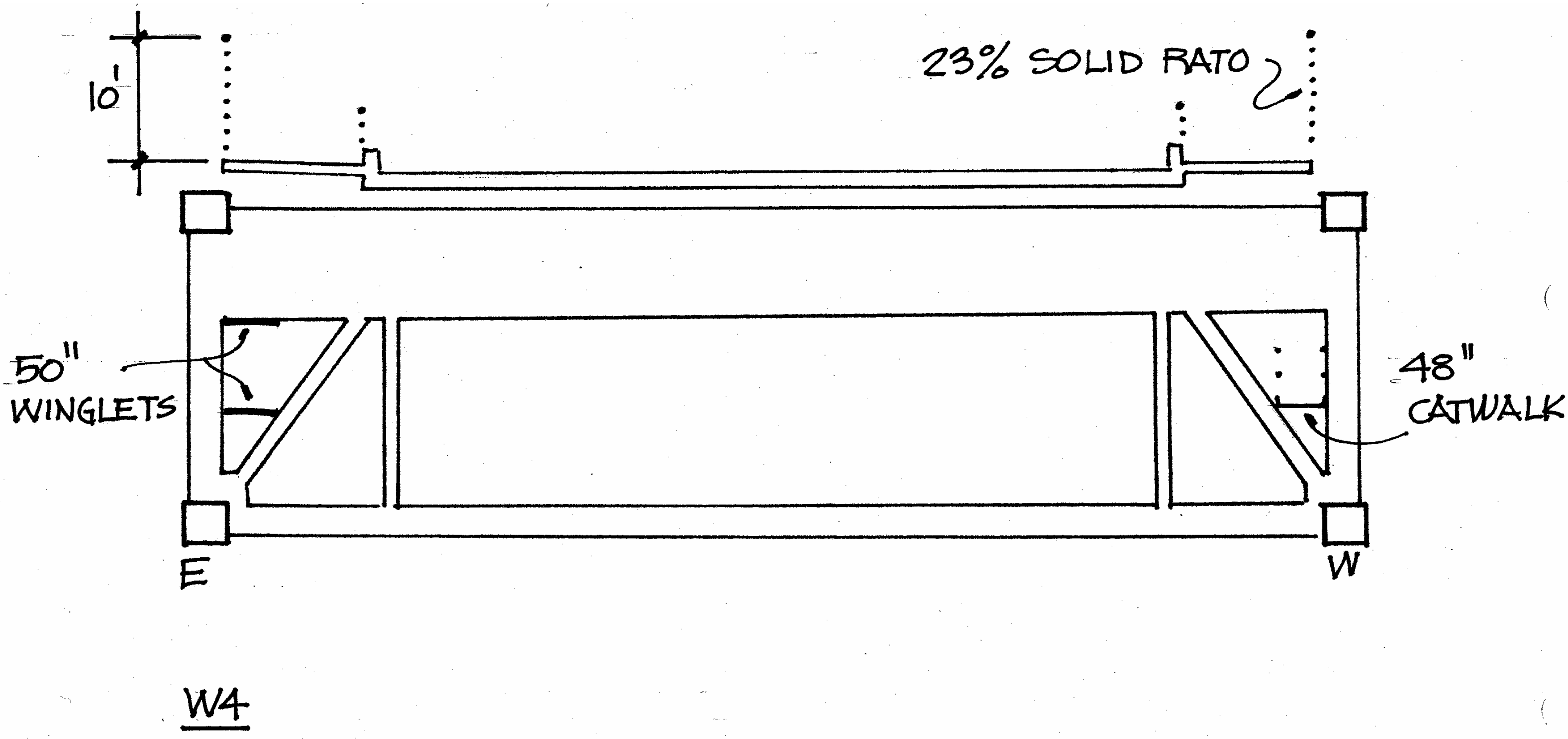


FIGURE C.5 - Similar to W1 except a new barrier height of 10’ instead of 12’

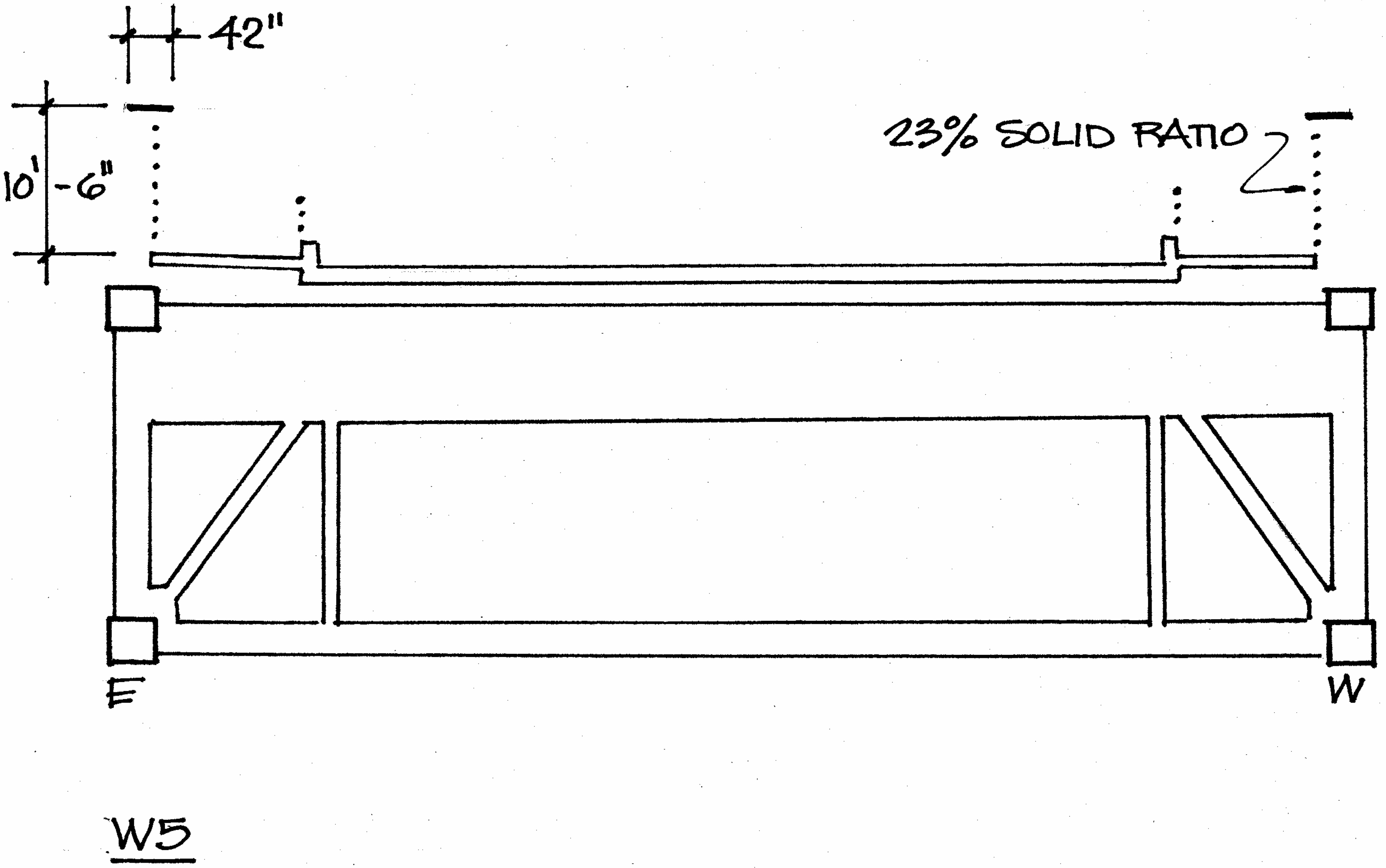


FIGURE C.6 - Similar to W2 except with a new barrier height of approximately 10’ and with a winglet mounted at 10’-6”

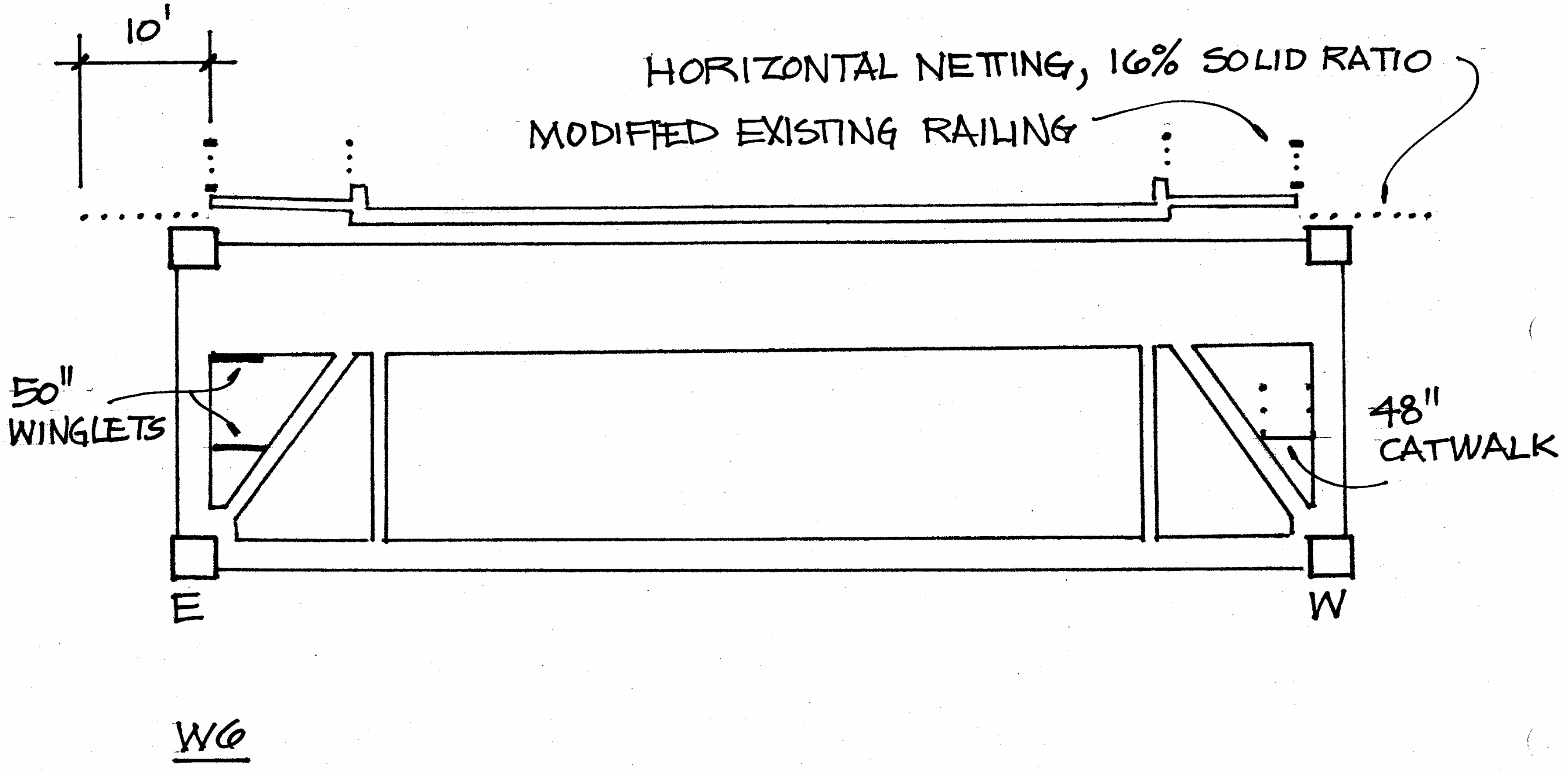
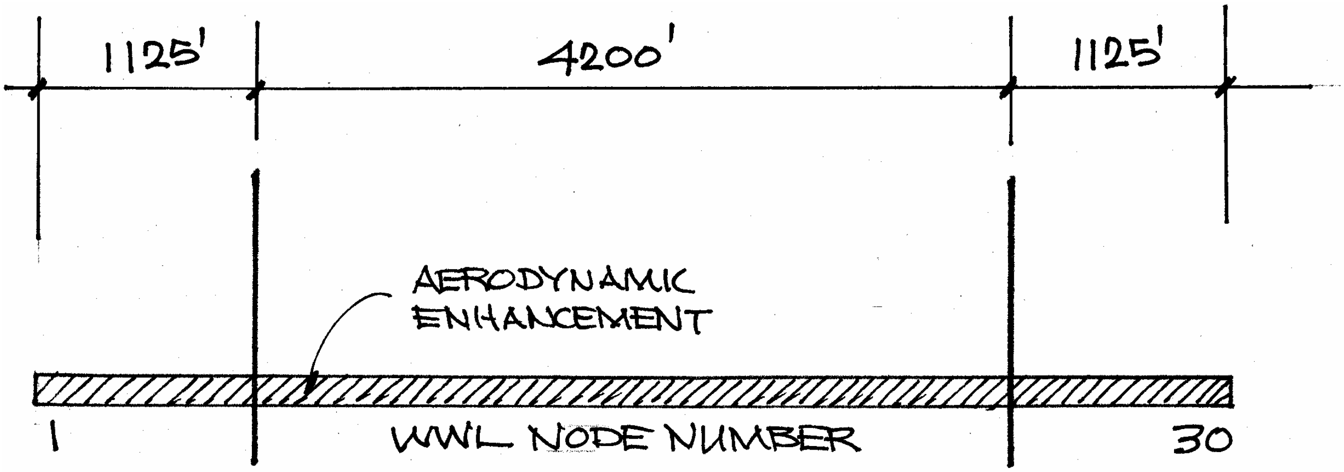
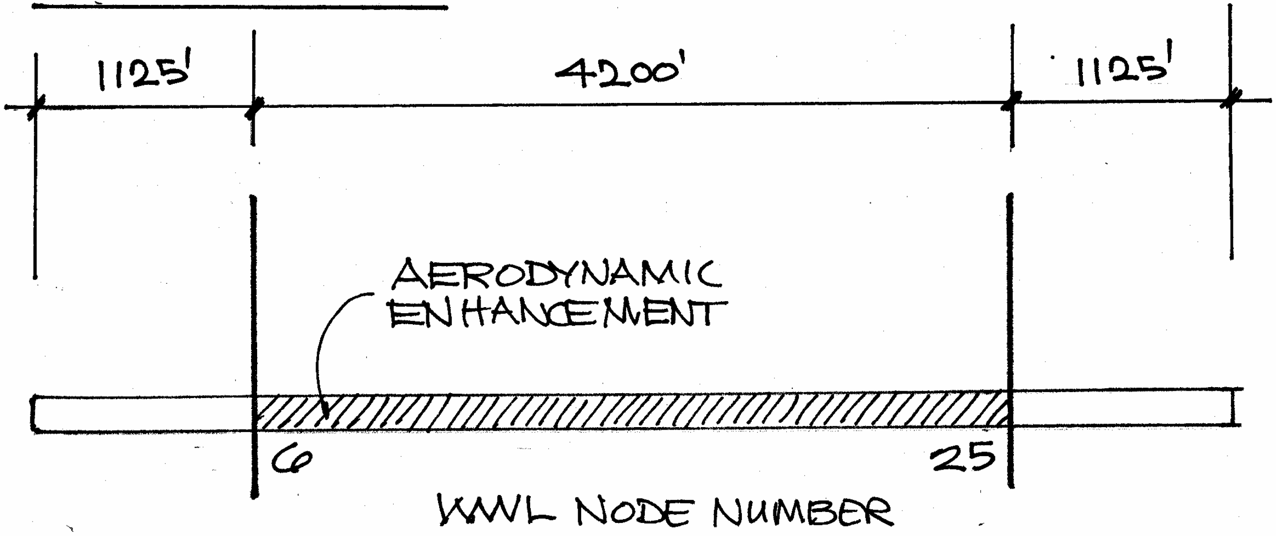


FIGURE C.7 - A horizontally projecting net. Net projection of 10' with a maximum solid ratio of 16%. Modify existing railing to have a maximum solid ratio of 23%. Below deck winglets and catwalk required

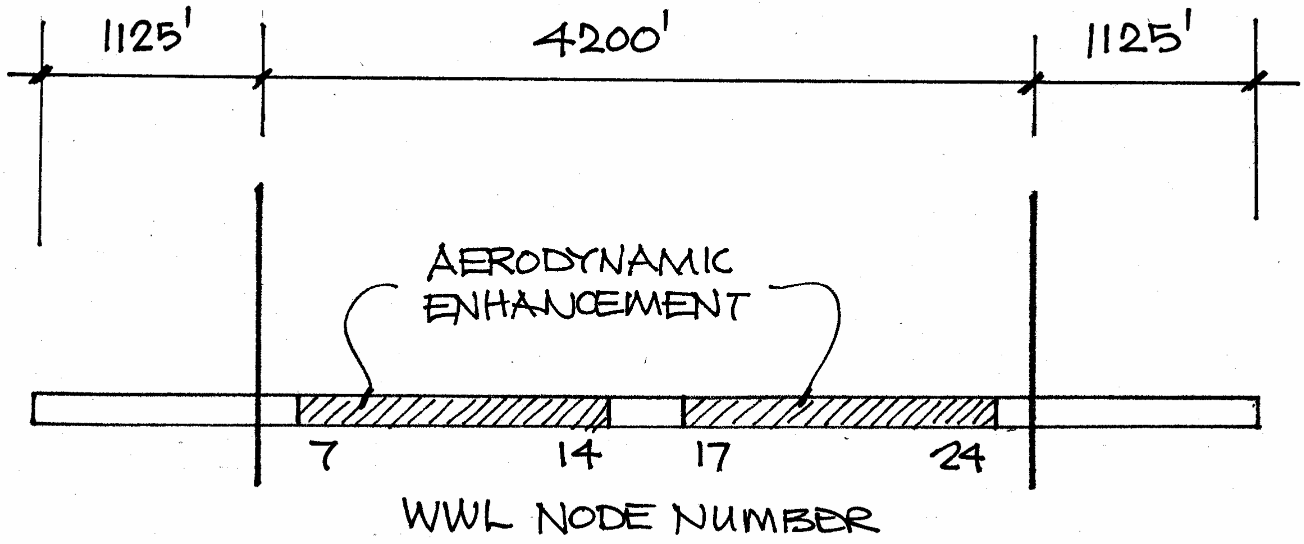


SPREAD CASE 0

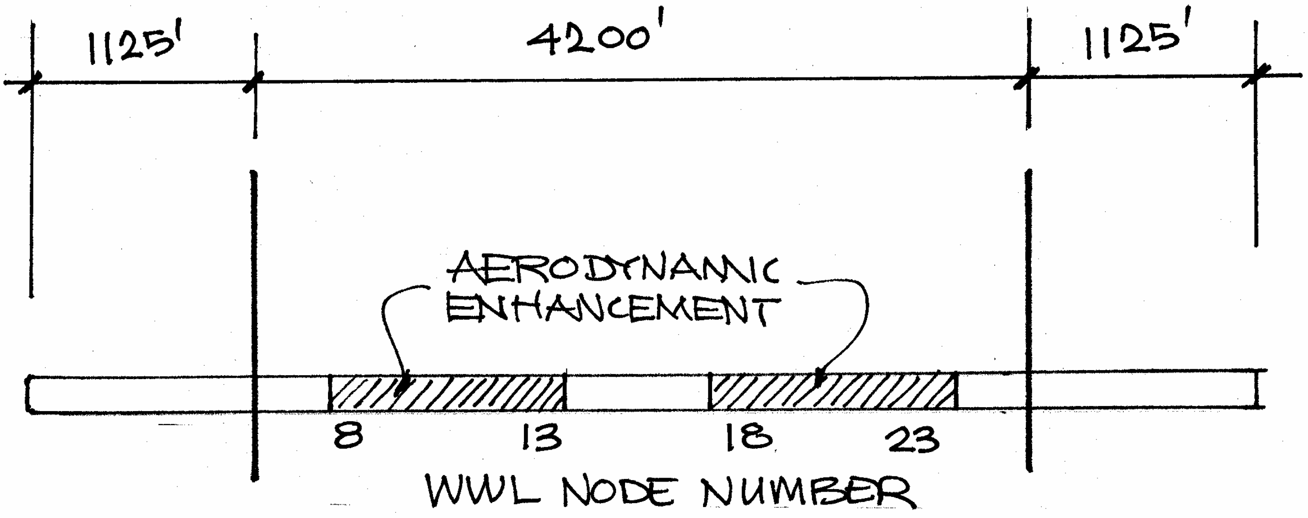


SPREAD CASE 1

FIGURE C.8



SPREAD CASE 2



SPREAD CASE 3

FIGURE C.9

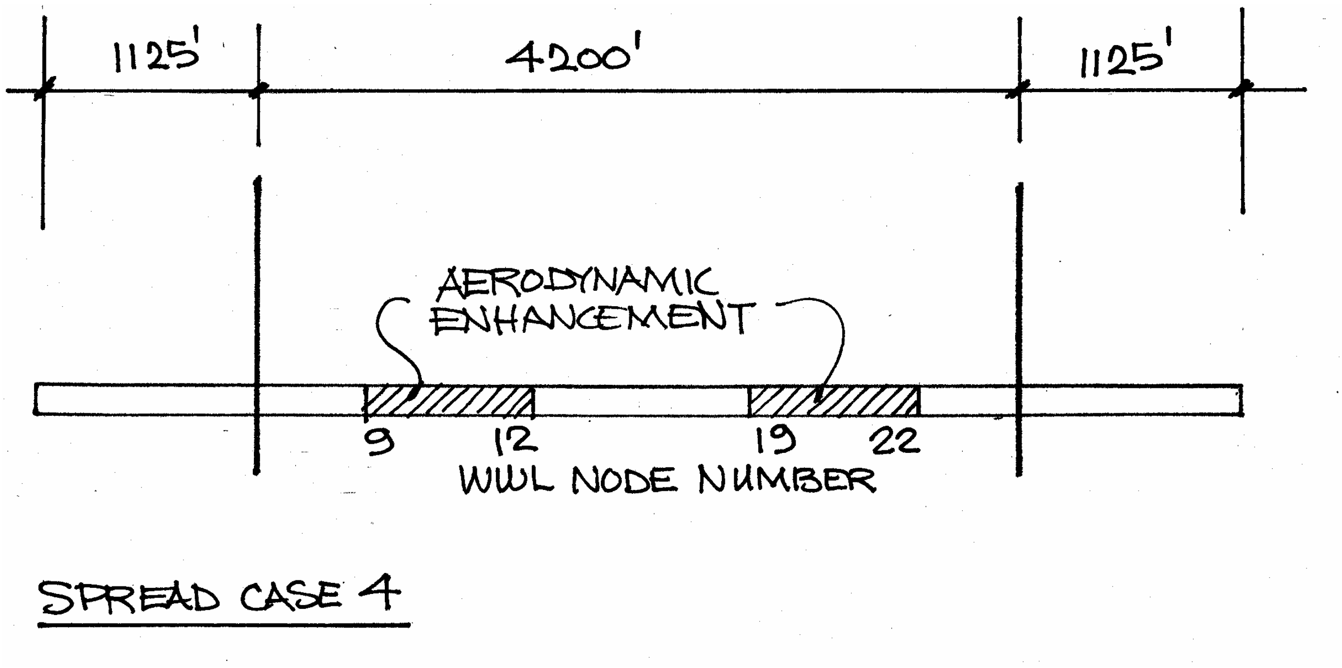

1125'
4200'
1125'
AERODYNAMIC ENHANCEMENT
9
12
19
22
WWL NODE NUMBER
SPREAD CASE 4

FIGURE C.10

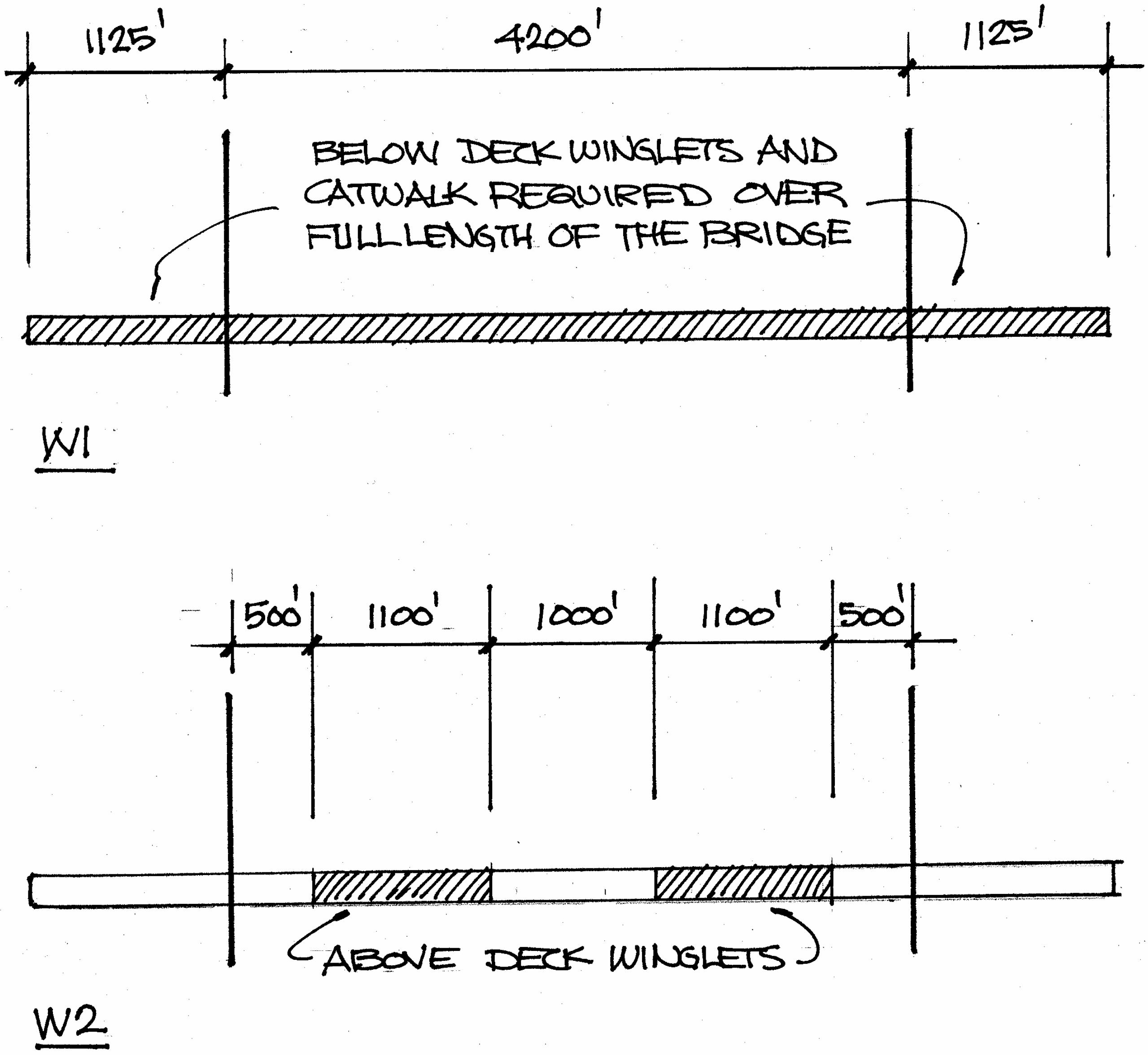
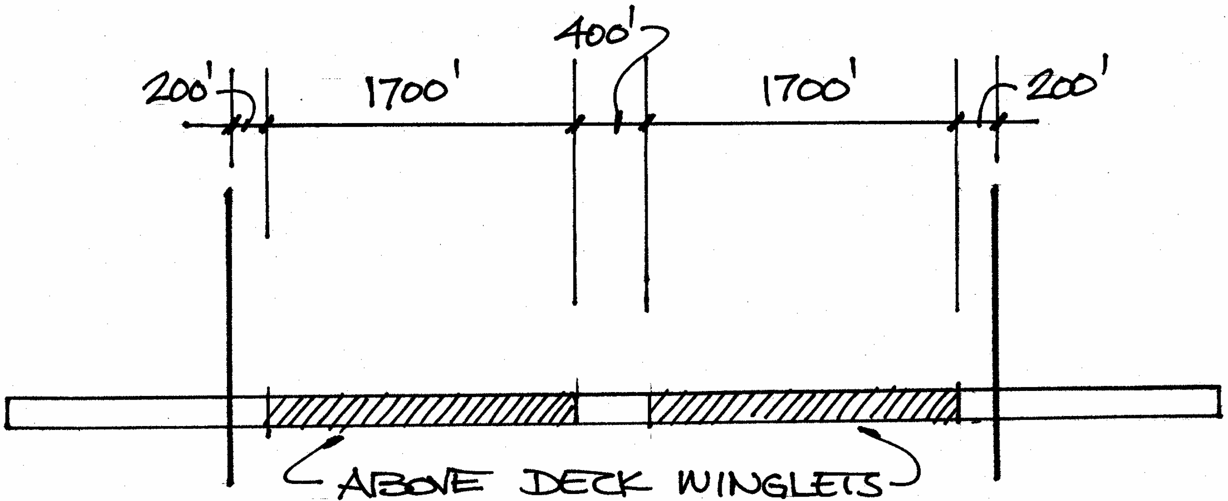
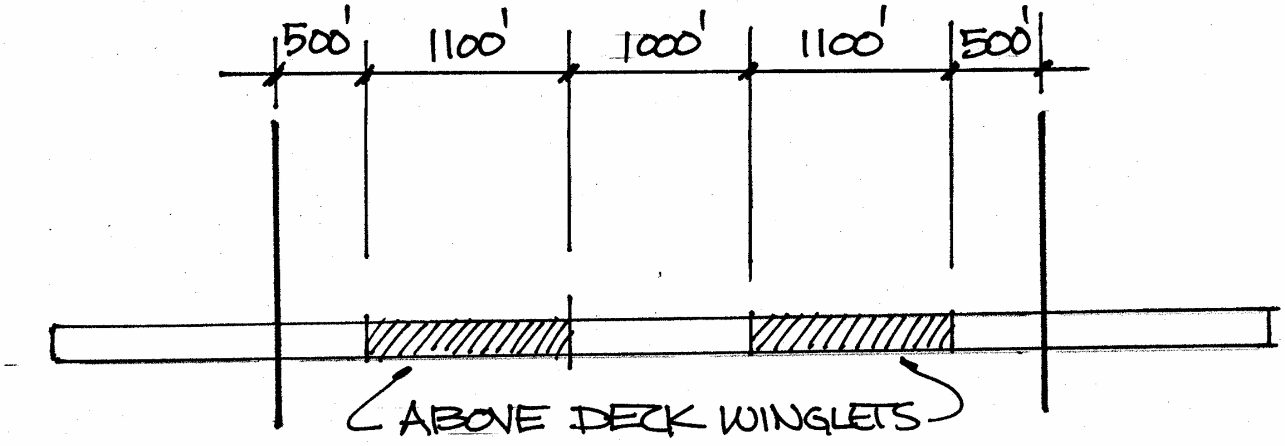

1125'
4200'
1125'
BELOW DECK WINGLETS AND CATWALK REQUIRED OVER FULLLENGTH OF THE BRIDGE
W1
500'
1100'
1000'
1100'
500'
ABOVE DECK WINGLETS
W2

FIGURE C.11

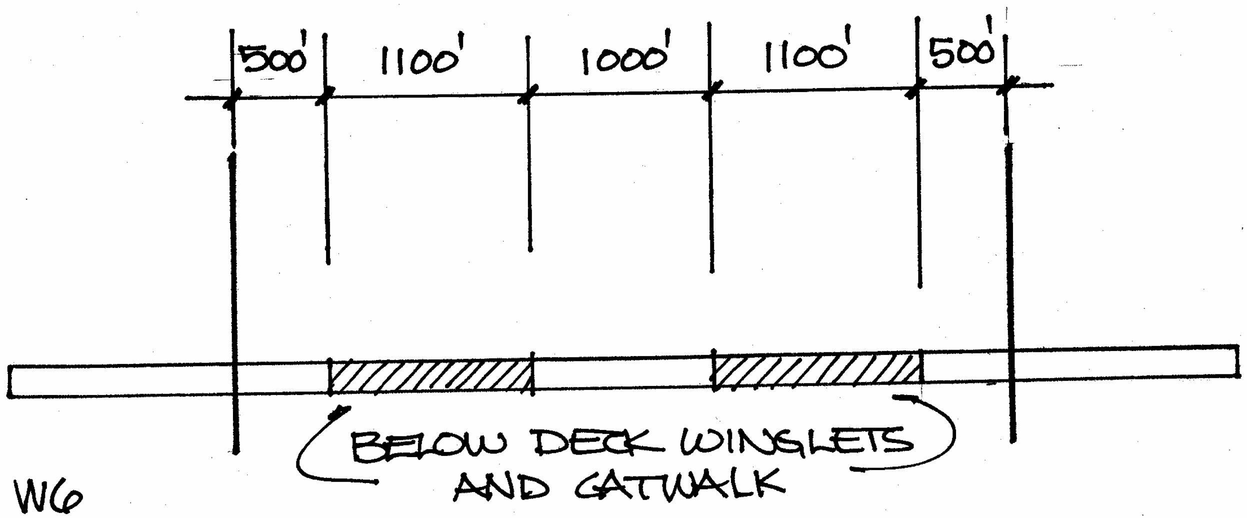


W3

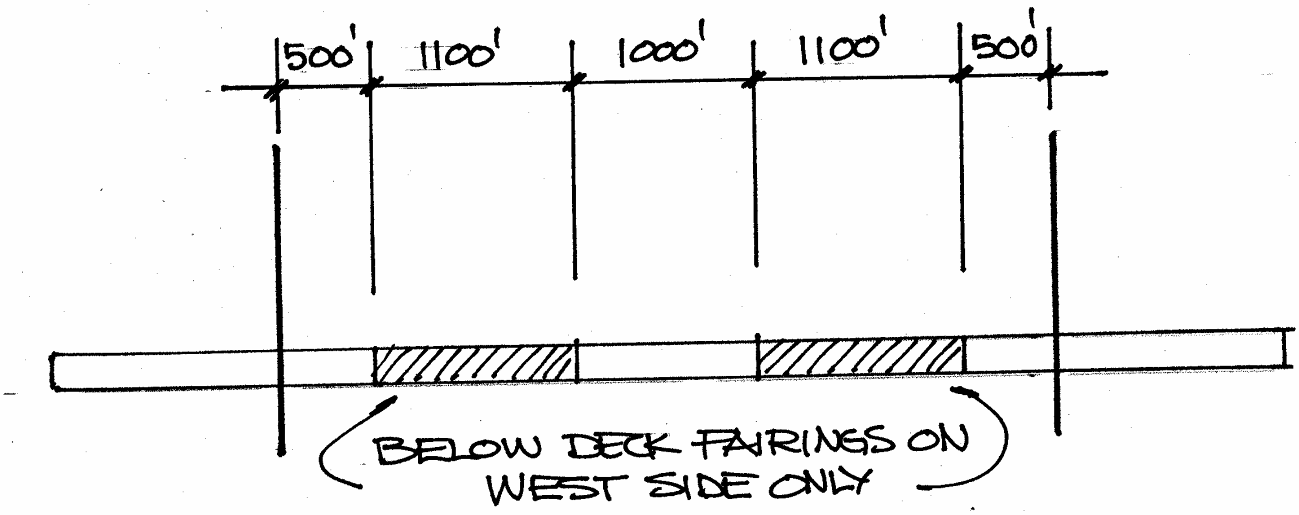


W5

FIGURE C.12



W6



W1 (ALTERNATE)

FIGURE C.13