INVESTIGATION OF OCCUPANT INDUCED DYNAMIC LATERAL LOADING ON EXTERIOR DECKS

By

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INVESTIGATION OF OCCUPANT INDUCED DYNAMIC

LATERAL LOADING ON EXTERIOR DECKS

Abstract

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Lateral loads on exterior decks caused by *occupant movement* can exceed those from extreme wind and seismic events. Occupant-induced dynamic loading is a function of the initial traction load, excitation frequency, and the stiffness and geometry of the deck system.

A finite element modeling (FEM) modal analysis was used to characterize dynamic load amplification as a function of the deck diaphragm stiffness, substructure stiffness, and the deck aspect ratio. An occupant traction load of 4 psf and excitation frequency of 1 Hz were assumed based on previous laboratory testing of decks loaded perpendicular to the ledger. Design curves and tables were developed to allow a designer to determine the amplification factor for a wide range of deck constructions.

A simplified design procedure was developed and implemented on a spreadsheet to calculate the unit shear demand on a deck diaphragm, as well as force demands on hold-downs and the deck frame. The predicted hold-down forces from the simplified procedure were compared to FEM analyses. For design adequacy checks, the predicted unit shear demand from the simplified method can be compared to the tabulated allowable design values published in Table 4.3D of the 2008 AWC *Special Design Provisions for Wind and Seismic (SDPWS)*.

Similarly, connection hardware solutions can be checked to meet the hold-down demand, and the deck substructure can be checked using the provisions of the 2012 AWC *National Design Specification for Wood Construction (NDS)*.

This study provides the tools necessary to perform lateral designs of decks, as well as inform the development of prescriptive design solutions for technical resources such as the *Design for Code Acceptance-6* (DCA6). Dowel-type fasteners (screws or threaded nails) were assumed for the deck board attachments. Proprietary “hidden” fasteners are gaining popularity for attaching deck boards. Some hidden fasteners allow slip, which can work well to accommodate longitudinal shrinkage and expansion caused by moisture and temperature changes; however, this slip can dramatically reduce deck diaphragm shear capacity and stiffness. Further research is needed to investigate ways to reinforce exterior deck systems to increase lateral stiffness and load carrying capacity.

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CHAPTER 1

DYNAMIC AMPLIFICATION OF LATERAL LOADS ON OUTDOOR DECKS DUE TO OCCUPANCY

1.1 Introduction

Each year there are numerous reports of residential deck failures. Often occurring suddenly, with no time to react, these collapses can cause personal injuries and occasionally, even death. While factors such as decayed members and corroded connections can increase the probability of a collapse, deck failures are usually the result of either inadequate guardrails or insufficient connections between the deck ledger and the side of the building (Carradine et al. 2007; 2008). Currently in the US it is estimated that there are over 40 million decks that are more than 20 years old (Shutt 2011). If we consider the millions of newer constructed decks in existence, with more of them being built every day, residential deck safety swiftly becomes a matter of the upmost importance.

From the design perspective, we can refer to Section R507.1 of the 2012 *International Residential Code* (IRC) and Section 1604.8.3 of the 2012 *International Building Code* (IBC). Both model codes state, "Where supported by attachment to an exterior wall, decks shall be positively anchored to the primary structure and designed for both vertical and lateral loads." While vertical (gravity) loads are well understood, designing for lateral loads are less certain. Wind and seismic forces on outdoor decks can be determined by using methods found in ASCE/SEI 7-10 (Lyman et al. 2013a; 2013b). Having no codified design procedures, the load case of lateral load due to occupancy is typically overlooked.

Previous research at Washington State University investigated the lateral load cases of wind, seismic, and occupancy, finding that occupancy can result in the governing lateral load case on an outdoor deck (Parsons et al. 2014b). Decks are not normally designed for lateral loads from occupancy, so further investigation was needed to better understand these loads and how they behave across a variety of deck configurations. Since building and testing numerous deck configurations in a laboratory is not feasible, structural analysis models were created using commercial finite element software. A modeling approach saves time and money compared to physically testing each deck configuration in a laboratory.

1.2 Objective

The objective of this study was to determine the forces in the deck framing and connections resulting from dynamic lateral loads caused by occupant movement, enveloped over a range of deck constructions and geometries, including:

- Deck board orientation (horizontal deck boards oriented parallel to the deck ledger and diagonal deck boards oriented at a 45-degree angle to the ledger).
- Deck board fastening system (dowel-type fastener)
- Varying degrees of deck substructure stiffness (e.g. resulting from embedded posts and knee braces)
- Deck aspect ratios (ranging from 1:2 to 2:1)

1.3 Literature Review

1.3.1 Determining Loads

A paper published in the Summer 2013 edition of the *Wood Design Focus* by Lyman et. al. explored lateral loads generated on a deck under wind loading. In particular, the paper highlights the changes in ASCE 7-10 to the wind chapter and provides a detailed example calculation using the updated methods. This example demonstrated that for a 12 ft. by 12 ft. deck, even after assuming the worst-case scenario, the lateral hold-downs would only need to each resist about 650 pounds. This is less than half of the 1500 pound minimum capacity given in Section R507.2.3 of the IRC.

Lyman et. al. (2013b) also investigated lateral loads generated on a deck due to seismic forces. Once again using ASCE 7-10, the same example deck was used to demonstrate the *equivalent lateral force* (ELF) method. The ELF method determines the seismic base shear and then uses an inverted triangular distribution to apply that shear to every floor of the structure. Similar to their wind load article, Lyman et. al. (2013b) found that the lateral hold-downs conservatively needed to each resist about 259 pounds when seismic loads govern.

After considering wind and seismic forces, most designers would not think to consider lateral loads generated by occupancy. People walking and moving about creates lateral loads on a deck, but currently there are no methods in ASCE 7-10 for determining such loads. Parsons et. al (2014b) experimentally determined these lateral loads for two deck constructions. The study addressed both cyclic and impulse loading on two different configurations of a 12 ft. by 12 ft deck: 1) deck boards were run parallel to the ledger, and 2) deck boards 45 degrees to the ledger. The results of these tests were quite surprising. In particular, the cyclic loads resulted in both large displacements and inertial forces, reaching a maximum displacement of ±7 inches when the swaying motion and deck boards were both parallel to the ledger. It was observed by Parsons et. al. (2014b) that once the deck started moving, the occupants were able to match their swaying rhythm to that of the deck at a frequency of approximately 1 Hz. When this occurred, it seemed easier for participants to remain in unison, since they could feel the motion of the deck and move along with it. When the deck boards are placed diagonally to the ledger, the deck is stiffened by a factor of 4 (Parsons et. al 2014b). Occupants had a harder time maintaining their swaying unison when they could not as easily feel the response of the deck under their feet.

These tests demonstrated that lateral loads due to occupancy cannot be ignored. While only certain regions of the country have wind or seismic forces that could potentially govern design, every deck has to deal with occupancy loading. Therefore, this means that more often than not, lateral loads from occupancy govern over wind and seismic load for the lateral design of residential decks. This is a load case not previously considered, lacking specific mention in any of the codes or design standards, with the exception of ASCE 7-10 Commentary Section C4.6, which mentions dynamic loading from crowds in grandstands or stadiums.

1.3.2 Deck Construction

Deck failures are usually the result of either inadequate guardrails or insufficient connections between the deck ledger and the side of the building. According to Loferski et. al., guardrail failures are usually due to the failure of the connection between the guardrail and the post. Rather than look at each deck component individually, a designer should be looking at the overall assembly and how the pieces work together (Loferski et. al 2010). In order to safely handle the design load of 200 lb concentrated load in any direction of the top rail, hold down hardware is typically required to anchor the post and to resist relatively large moments from the rail forces.

Due to lack of structural redundancy, when a deck ledger pulls away from the primary structure, the entire deck can collapse. When deck ledger attachment provisions were added to the 2009 IRC, a lateral tie-down requirement was also added based on engineering judgment. The *Design for Code Acceptance 6* (DCA 6) (AF&PA 2010), which is based off of the IRC, also includes the hold-down provision. The hold-down requirement was based on engineering judgment (Lyman et. al. 2013a). While the previously discussed research showed that the 1500 lb minimum capacity for the hold-downs is conservative in the case of wind and seismic loads for one deck dimension scenario, Parsons et. al. chose to focus on the hold-downs and lateral load from occupancy load. To conduct the tests for this experiment, a simulated house diaphragm was constructed following all of the respective code regulations. To simulate the effect of occupancy lateral load, a steel channel was used as a drag strut to evenly allocate the force across the surface of the model decks. Joist hangers with a fastener pattern that install fasteners perpendicular to member faces were implemented, along with manufacturer approved screws (Parsons et. al. 2014a)

The simulated deck system was tested with and without the required hold-downs in order to compare the differences between the two. Oddly enough, the hold-downs performed in a way contrary to how they were predicted to behave, due to flexible deck diaphragms that allowed significant joist rotation in the joist hanger. For example, the hold-down installed on the compression chord actually ended up carrying a considerable amount of tension until the chord failed. Parsons et. al. theorized that the hold-downs might have been more effective if the deck was stiffer. The stiffness could have been increased by switching the deck boards to a diagonal orientation (Parsons et. al 2014a; Parsons et. al. 2014b). Additionally, it was found that with a second type of joist hanger – one that uses a toe-nail type fastener pattern and would typically be installed on a deck – the joists pulled out of their hangers and the lateral hold-downs performed as planned. Some experts argue that this type of connection to the ledger violates the code requirement that nails not be loaded in withdrawal. Others in the deck industry do not interpret the requirement in this manner. Bottom line, some sort of hardware is needed to provide a positive load path especially when smooth shank nails are used to attach the joist hangers.

1.4 Model Development

As a cheaper, faster alternative to building and testing multiple deck configurations in the laboratory, deck models were created using ABAQUS, a commercial finite element program. ABAQUS was chosen for its power and versatility, capable of several different types of analyses. This includes static/dynamic analysis, natural frequency extraction, and nonlinear behavior. ABAQUS provided the flexibility to adjust the models to be simpler or more complex as the project progressed. The decks were modeled using simple, Euler-Bernoulli beam elements for all wood members. Constant rectangular cross sections, isotropic material properties, and a 5% damping ratio were conservatively assumed for all members. A sensitivity analysis was performed on the damping ratio, varying from 5% up to 12.5%. It was observed that the results of the models with 5% damping ratio closely matched the results of the previous physical deck tests in the laboratory. Interested in only the linear-elastic behavior of the deck models, the 5% damping ratio calibrated the linear FEM models to match the non-linear behavior observed in the previous laboratory tests.

A total of twelve deck models were created to explore the effect of aspect ratio and deck board orientation. Six different aspect ratios were tested, ranging from 1:2 along the primary building (7.32 m by 3.66 m, or 24 ft by 12 ft) to 2:1 away from the primary building (3.66 m by 7.32 m, or 12 ft by 24 ft). For each aspect ratio, two different deck board configurations were tested; horizontal deck boards parallel to the ledger (Figure 1.1, Figure 1.2) and diagonal deck boards oriented 45 degrees to the ledger (Figure 1.3, Figure 1.4). Based on previous research by Parsons et al., the deck ledgers were modeled as two 2x12 pieces of lumber, joists were 2x10 spaced 0.41 m (16 inches) on center, and the deck boards were 2x6 with a 0.25 inch gap between members (Parsons et al. 2014b). The models did not account for bearing between deck boards. All of the beam elements were given the properties of No.2, Hem-fir lumber at 12% moisture content.

Springs were used to connect the beam elements, modeling the stiffness properties of Simpson Strong-Tie Structural-Connector screws, derived in Appendix B. The springs connecting the joists to the ledgers were equivalent in stiffness to sixteen, #9 screws used with a Simpson Strong-Tie hanger Model No. LU210. This hanger utilizes a fastener pattern that places the screws perpendicular to member faces (Parsons et al. 2014b). The springs connecting deck boards to the joists were equivalent in stiffness to two, #8 screws spaced 3.5 inches apart. Rigid links were used to create connection points at realistic offsets from the centerline of the members. Each deck model was pinned along one ledger to represent lag bolt attachment to the primary structure.

The assumed spring coefficients were determined using the load/slip modulus equation found in Section 10.3.6 of the NDS (AWC 2012). For dowel-type fasteners:

$$\gamma = (180{,}000)(D^{1.5}) \qquad \text{for wood-to-wood connections}$$
$$\gamma = (270{,}000)(D^{1.5}) \qquad \text{for wood-to-metal connections}$$

“D” (inches) is equal to the diameter of the dowel-type fastener. For #8 screws that connect the deck boards to the joists, a diameter of 0.164 inches yields a slip modulus of 11955 lb/in. The #9 screws connecting the joist hangers have a diameter of 0.177 in and a slip modulus of 20106 lb/in. The slip modulus is multiplied by the number of fasteners in the connection to get the total stiffness that should be entered into the model as a spring stiffness coefficient. For example, for each pair of fasteners connecting the deck boards to the joists, a spring coefficient of 23909 lb/in was used for translational degrees of freedom (x- and z-axis in the model orientation). For a derivation of the rotational stiffness for deck board fasteners, see Appendix B.

1.5 Model Analysis

Each deck model was analyzed three ways: static, frequency, and steady-state modal dynamic. For all three analyses, an initial traction load of 4 psf was applied, representing the uniform lateral surface traction generated by a 40 psf occupancy load. This was determined from the previous study by Parsons et. al. (2014b) for when the cyclic load was applied perpendicularly to the deck ledger and board orientation. The high diaphragm stiffness of this configuration resulted in hardly any deflection when loaded with 40 psf occupancy with cyclic motion, thus indicating the near maximum traction load that could be developed by occupants with negligible dynamic amplification.

For the static analysis, the surface traction load was applied and the reactions were measured along the ledger. This was essentially pulling on the deck with a 4 psf load and predicting the resulting member displacements and reaction forces (Parsons et al. 2014a). The frequency analysis served two purposes. First, the analysis determined the natural frequencies and mode shapes for any given number of modes. Secondly, the frequency analysis determined the eigenvalues associated with each of those modes, which were then used in the dynamic analysis. The particular type of dynamic analysis used in this investigation cannot work without the modal eigenvalues. It should be noted that a sufficient number of eigenvalues need to be extracted for the reaction forces to converge. The level of convergence is subject to individual engineering judgment (Dassault Systèmes 2013). For this study, extracting eigenvalues for roughly 20% of the total number of degrees of freedom contained in the model was found to provide adequate convergence. For example, the 12 ft. by 12 ft. horizontal deck model had a total of 2,841 elements and 8,523 degrees of freedom. Therefore, 1,700 eigenvalues were extracted to achieve reasonable convergence.

Steady-state modal analysis provides the response of the deck when excited at a particular frequency. A frequency sweep applies the load cyclically over a range of different frequencies (Dassault Systèmes 2013). From the previous research, it was observed that occupants generating a cyclic lateral load could achieve a maximum frequency of 1 Hz (Parsons et al. 2014b). Thus a frequency sweep from 0 to 1 Hz was applied for each deck model. The outcome is a plot of the deck's response at each frequency in the sweep (Figure 1.5). Different parameters can be plotted on the y-axis, including nodal displacements and reaction forces. Each deck configuration was analyzed multiple times with the independent variable being the total substructure stiffness. For further discussion of these frequency sweeps, see Appendix A.

1.6 Results and Discussion

1.6.1 Dynamic Amplification – Design Curves

As expected, the steady-state modal analysis illustrated the critical role of deck mass in the dynamic structural response. When a lateral occupancy load is cyclically applied to a deck, dynamic amplification of the deck's forces and deflections occurs. This amplification is dependent on the natural frequency of the system, which in turn depends on stiffness. If the diaphragm has low stiffness (horizontal deck boards) and little to no substructure, the deck's response is dynamically amplified by a factor of around 4 (Table 1.1). A diaphragm with high stiffness (diagonal deck boards) or high substructure stiffness yields little to no dynamic amplification (Table 1.7). Interestingly, an amplification of 4 closely compares to the results Parsons et. al. (2014b) observed while physically testing the same deck configuration in the laboratory.

It was determined that a unitless dynamic amplification factor would be useful for designers when determining the design lateral load due to occupancy. The steady-state modal analysis results were combined and normalized into a dynamic amplification factor, designated as C_k. This was accomplished by dividing the dynamic results at 1 Hz by the static results at 0 Hz. For example, we can refer to the case of 1:1 aspect ratio with horizontal deck boards and no substructure (Table 1.1). At 0 Hz, which is equivalent to the static analysis, the total resultant shear force in the ledger is 600 lbs, or the 4 psf load across the area of the nominal 12 ft. by 12 ft. deck (actual deck area was 150 ft^2 due to assumed board layout). At 1 Hz, the response of the same deck configuration is 2488 lbs. The ratio between these two reactions is 4.147, meaning the deck's mass under cyclic lateral loading was free to displace enough to generate forces over 4x greater than for the static case. As expected, Table 1.1 shows that as substructure stiffness increases, the natural frequency increases. Higher stiffness resists the movement of the mass and causes the dynamic amplification factor to decrease. If the substructure were to become infinitely stiff, the dynamic results would perfectly match the static results and the dynamic amplification factor would become 1.0.

These dynamic amplification factors can also be plotted as a series of design curves. One set of curves was created for horizontal deck boards (Figure 1.6) and another for diagonal deck boards (Figure 1.7, Figure 1.8). A designer separately determines the total substructure stiffness, selects the appropriate design curve for their particular aspect ratio, and can determine the dynamic amplification factor for that deck configuration. Note that as the aspect ratio moves away from the primary structure (i.e., 1.5:1, 2:1) the dynamic amplification increases due to the increased moment arm. Tables 1.1-1.6 tabulate the data used to create the horizontal design curves, while Tables 1.7-1.12 contain the information for the diagonal design curves. Additional explanation of the design curves can be found in Appendix A.

1.6.2 Design Procedure

Given the substructure stiffness, dimensions, and board orientation of a deck, a designer can easily determine the structure's behavior under occupancy lateral loading. For example, consider a 12 ft. by 12 ft. deck with horizontal deck boards. The deck is supported by 8 ft tall 6x6 No. 2 Hem-Fir posts, each with a single 2x4 knee brace. The total substructure stiffness of these posts is approximately 800 lb/in. Using the design curves for horizontal deck boards (Figure 1.6), we can see that that substructure on a 1:1 aspect ratio has a dynamic amplification factor of about 1.7. The lateral occupancy design load, w is equal to (4 psf)*C_k, so for this example w = (4 psf)*(1.7) = 6.8 psf. This new load replaces 4 psf in the static hand calculations used to determine reaction forces. Chapter 2 introduces a simplified design procedure for determining reaction forces by examining compatibility of deflection between the diaphragm and the substructure.

1.7 Summary and Conclusions

With physical decks being costly and time consuming to test in a laboratory, structural analysis models were used to determine the effects of lateral loads due to occupancy. A variety of deck configurations were analyzed, varying aspect ratio, board orientation, and substructure stiffness. It was determined that dynamic amplification of the deck's mass plays a critical role is in the structural response under cyclic occupant loading. A unitless dynamic amplification factor was created and plotted on a series of design curves to help designers quickly determine the amplification factor for a particular deck configuration. The amplified lateral occupancy load is then included in the design by using simple statics.

From this study, we can conclude that dynamic amplification of lateral occupancy loads on an outdoor deck is an issue that cannot be ignored. There are a few simple solutions to reduce a deck's dynamic amplification factor. First, the substructure stiffness can be increased. Adding larger posts, more posts, embedding the posts, more knee braces, or decreasing post height are all potential options for increasing substructure stiffness. Second, the diaphragm stiffness/capacity can be increased by switching from horizontal deck boards to diagonal deck boards. Structural diaphragms using diagonal deck boards are 4x stiffer than those with horizontal boards, putting the amplification near 1.0 for aspect ratios along the length of the primary structure. Third, the deck dimensions/aspect ratio can be changed.   Decreasing the distance away from the primary structure and/or decreasing the length along the primary structure results in a smaller amplification factor. Smaller decks have smaller amplifications due to reduced mass. By statics, shortening the moment arm, the distance away from the building, has a bigger impact on dynamic amplification than the width of the deck along the building.

Further research is needed to investigate ways to increase the lateral stiffness of exterior deck systems. The stiffness of a deck diaphragm was shown to have profound impacts on dynamic amplification of lateral loads, while at the same time flexible decks have low diaphragm strength. While some methods of increasing stiffness were previous discussed, there are several more methods that still need to be examined. While the models only looked at posts with knee braces, other methods that could be investigated include cross bracing, steel straps, cables, or perhaps sheathing. The models created for this project only scratched the surface of potential deck configurations. Deck posts of varying heights, such as decks extending out over a slope, is one example that could be tested. Another issue is stairs, which could provide significant stiffness to the deck system depending on the placement.

Beyond deck board orientation, there are also several other species of wood or alternative materials that could have tested. Of particular interest to the deck construction industry is the performance of composite lumber. Composite deck boards have different structural properties, densities, and attachment methods such as hidden fasteners. Some hidden fasteners that are gaining popularity employ a tab that engages a slot on the side of the deck boards, allowing slip. The slip can be a good feature to accommodate longitudinal shrinking/swelling of the boards caused by moisture and temperature changes, but it can also result in significantly lower diaphragm shear capacity and stiffness. In these cases, the system stiffness needs to be restored by some other means.

Additionally, the finite element models developed in this study used spring stiffnesses equivalent to common deck screws. Many decks are constructed using nails, which have different stiffness properties than screws. Furthermore, the attachment of the joists to the ledgers was modeled after hangers that used fasteners perpendicular to member faces. Using traditional hangers that are toe-nailed together results in reduced stiffness due to issues with withdrawal. When a significant lateral load is applied, the toe-nailed joists pull right out of their hangers. Future work could examine methods of reinforcing decks constructed using nails to better resist lateral loading.

Similarly, this study used linear springs when modeling deck fasteners and isotropic properties for the wood. In reality, both the fasteners and lumber had non-linear behavior. This is reflected when comparing model results to laboratory tests conducted in previous research. Modeling non-linear and orthotropic deck properties is possible, but not without more time and effort invested into developing those models. If more model refinement is deemed necessary, further research could invest resources into creating even more realistic models.

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1.9 Tables

Table 1.1 Model Results: 1:1 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.951	600	2488	2669	11069	**4.15**
200	35	1.119	600	2065	2669	9185	**3.44**
300	53	1.189	600	1618	2669	7199	**2.70**
400	70	1.252	600	1382	2669	6149	**2.30**
600	105	1.362	600	1148	2669	5109	**1.91**
800	140	1.454	600	1034	2669	4600	**1.72**
1000	175	1.533	600	967	2669	4300	**1.61**
1200	210	1.600	600	922	2669	4103	**1.54**
1800	315	1.755	600	849	2669	3778	**1.42**
2200	385	1.829	600	823	2669	3662	**1.37**
3200	560	1.956	600	787	2669	3499	**1.31**
4200	736	2.035	600	768	2669	3415	**1.28**
5200	911	2.087	600	756	2669	3363	**1.26**
6500	1138	2.133	600	746	2669	3320	**1.24**
4.0E+09	7.0E+08	2.329	600	708	2669	3148	**1.18**

Table 1.2 Model Results: 1:1.5 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.941	933	3869	4152	17211	**4.15**
200	35	1.056	933	3974	4152	17675	**4.26**
300	53	1.107	933	3378	4152	15024	**3.62**
400	70	1.154	933	2821	4152	12548	**3.02**
600	105	1.238	933	2220	4152	9876	**2.38**
800	140	1.313	933	1924	4152	8558	**2.06**
1000	175	1.379	933	1751	4152	7787	**1.88**
1200	210	1.438	933	1637	4152	7284	**1.75**
1800	315	1.582	933	1454	4152	6466	**1.56**
2200	385	1.658	933	1388	4152	6175	**1.49**
3200	560	1.797	933	1298	4152	5773	**1.39**
4200	736	1.892	933	1251	4152	5566	**1.34**
5200	911	1.958	933	1223	4152	5439	**1.31**
6500	1138	2.020	933	1199	4152	5334	**1.28**
4.0E+09	7.0E+08	2.303	933	1105	4152	4917	**1.18**

Table 1.3 Model Results: 1:2 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.938	1200	4974	5338	22125	**4.14**
200	35	1.029	1200	5064	5338	22527	**4.22**
300	53	1.071	1200	4981	5338	22156	**4.15**
400	70	1.109	1200	4296	5338	19111	**3.58**
600	105	1.181	1200	3322	5338	14777	**2.77**
800	140	1.245	1200	2814	5338	12517	**2.34**
1000	175	1.303	1200	2515	5338	11189	**2.10**
1200	210	1.356	1200	2321	5338	10324	**1.93**
1800	315	1.489	1200	2007	5338	8928	**1.67**
2200	385	1.561	1200	1897	5338	8436	**1.58**
3200	560	1.702	1200	1744	5338	7759	**1.45**
4200	736	1.801	1200	1666	5338	7412	**1.39**
5200	911	1.875	1200	1619	5338	7200	**1.35**
6500	1138	1.900	1200	1579	5338	7024	**1.32**
4.0E+09	7.0E+08	1.901	1200	1424	5338	6334	**1.19**

Table 1.4 Model Results: 1.5:1 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.630	912	3873	4058	17226	**4.25**
200	35	0.753	912	3923	4058	17451	**4.30**
500	88	0.898	912	3994	4058	17766	**4.38**
750	131	0.995	912	4048	4058	18004	**4.44**
1000	175	1.078	912	3923	4058	17451	**4.30**
1500	263	1.212	912	2418	4058	10757	**2.65**
2500	438	1.403	912	1712	4058	7614	**1.88**
3500	613	1.531	912	1504	4058	6690	**1.65**
4500	788	1.623	912	1405	4058	6249	**1.54**
5500	963	1.690	912	1347	4058	5991	**1.48**
6500	1138	1.743	912	1309	4058	5822	**1.43**
4.0E+09	7.0E+08	2.129	912	1123	4058	4997	**1.23**

Table 1.5 Model Results: 1.75:1 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.545	1056	4509	4697	20058	**4.27**
200	35	0.667	1056	4576	4697	20355	**4.33**
400	70	0.763	1056	4638	4697	20630	**4.39**
600	105	0.844	1056	4694	4697	20882	**4.45**
800	140	0.913	1056	4746	4697	21110	**4.49**
1000	175	0.972	1056	4792	4697	21315	**4.54**
1200	210	1.025	1056	4805	4697	21375	**4.55**
1400	245	1.072	1056	4749	4697	21123	**4.50**
1500	263	1.094	1056	4376	4697	19465	**4.14**
1600	280	1.115	1056	4013	4697	17852	**3.80**
1700	298	1.134	1056	3707	4697	16488	**3.51**
2000	350	1.187	1056	3077	4697	13689	**2.91**
2500	438	1.261	1056	2541	4697	11303	**2.41**
3500	613	1.369	1056	2096	4697	9324	**1.98**
4500	788	1.445	1056	1903	4697	8465	**1.80**
5500	963	1.501	1056	1795	4697	7986	**1.70**
6500	1138	1.543	1056	1727	4697	7680	**1.63**
4.0E+09	7.0E+08	1.854	1056	1413	4697	6286	**1.34**

Table 1.6 Model Results: 2:1 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.480	1200	5145	5339	22886	**4.29**
200	35	0.587	1200	5201	5339	23133	**4.33**
400	70	0.673	1200	5254	5339	23371	**4.38**
600	105	0.746	1200	5305	5339	23598	**4.42**
800	140	0.809	1200	5353	5339	23812	**4.46**
1000	175	0.865	1200	5398	5339	24011	**4.50**
1200	210	0.914	1200	5439	5339	24195	**4.53**
1400	245	0.959	1200	5477	5339	24362	**4.56**
1500	263	0.980	1200	5494	5339	24440	**4.58**
1600	280	0.999	1200	5511	5339	24514	**4.59**
1700	298	1.018	1200	5572	5339	24783	**4.64**
2000	350	1.070	1200	5474	5339	24352	**4.56**
2500	438	1.143	1200	4090	5339	18194	**3.41**
3500	613	1.253	1200	2936	5339	13061	**2.45**
4500	788	1.332	1200	2513	5339	11177	**2.09**
5500	963	1.392	1200	2296	5339	10213	**1.91**
6500	1138	1.437	1200	2165	5339	9629	**1.80**
4.0E+09	7.0E+08	1.786	1200	1626	5339	7232	**1.35**

Table 1.7 Model Results: 1:1 aspect ratio, diagonal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	3.221	589	624	2619	2778	**1.06**
200	35	3.268	580	613	2579	2729	**1.06**
6500	1138	4.309	441	452	1961	2010	**1.03**
4.0E+09	7.0E+08	4.347	297	299	1319	1328	**1.01**

Table 1.8 Model Results: 1:1.5 aspect ratio, diagonal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	2.791	919	941	4088	4184	**1.02**
200	35	2.791	916	937	4074	4168	**1.02**
6500	1138	2.808	835	851	3715	3783	**1.02**
4.0E+09	7.0E+08	2.878	474	477	2109	2121	**1.01**

Table 1.9 Model Results: 1:2 aspect ratio, diagonal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	2.037	1183	1206	5264	5366	**1.02**
200	35	2.037	1181	1204	5253	5354	**1.02**
6500	1138	2.043	1112	1130	4947	5028	**1.02**
4.0E+09	7.0E+08	2.083	622	624	2766	2777	**1.00**

Table 1.10 Model Results: 1.5:1 aspect ratio, diagonal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.913	897	2739	3989	12182	**3.05**
200	35	1.009	814	1149	3621	5110	**1.41**
6500	1138	2.293	511	552	2272	2457	**1.08**
4.0E+09	7.0E+08	2.665	448	460	1991	2046	**1.03**

Table 1.11 Model Results: 1.75:1 aspect ratio, diagonal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.692	1041	3663	4630	16294	**3.52**
200	35	0.799	949	3203	4221	14246	**3.38**
800	140	1.042	827	2628	3679	11689	**3.18**
900	158	1.075	816	2493	3628	11089	**3.06**
1000	175	1.106	805	2189	3582	9738	**2.72**
1100	193	1.137	796	1936	3540	8610	**2.43**
1200	210	1.166	787	1745	3503	7761	**2.22**
1300	228	1.193	780	1600	3468	7119	**2.05**
1400	245	1.220	773	1489	3437	6623	**1.93**
1500	263	1.246	766	1400	3408	6230	**1.83**
2000	350	1.363	739	1142	3289	5078	**1.54**
2500	438	1.464	719	1015	3200	4516	**1.41**
3500	613	1.632	691	888	3073	3950	**1.29**
4500	788	1.765	671	822	2984	3658	**1.23**
5500	963	1.875	656	781	2917	3475	**1.19**
6500	1138	1.966	644	753	2864	3348	**1.17**
4.0E+09	7.0E+08	2.136	529	566	2353	2520	**1.07**

Table 1.12 Model Results: 2:1 aspect ratio, diagonal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.563	1184	4255	5265	18925	**3.59**
200	35	0.659	1088	3778	4840	16807	**3.47**
750	131	0.858	991	3326	4408	14796	**3.36**
800	140	0.873	987	3309	4389	14718	**3.35**
900	158	0.902	979	3279	4356	14587	**3.35**
1000	175	0.929	973	3256	4329	14484	**3.35**
1100	193	0.956	968	3238	4306	14404	**3.35**
1200	210	0.981	964	3224	4287	14342	**3.35**
1300	228	1.005	960	3215	4271	14303	**3.35**
1400	245	1.029	957	3199	4257	14232	**3.34**
1500	263	1.051	691	1799	3076	8001	**2.60**
2000	350	1.152	659	1274	2931	5666	**1.93**
2500	438	1.240	637	1021	2835	4541	**1.60**
3500	613	1.384	610	831	2716	3698	**1.36**
4500	788	1.501	595	755	2645	3359	**1.27**
5500	963	1.598	584	714	2599	3177	**1.22**
6500	1138	1.679	577	689	2566	3064	**1.19**
4.0E+09	7.0E+08	1.763	532	573	2366	2547	**1.08**

1.10 Figures

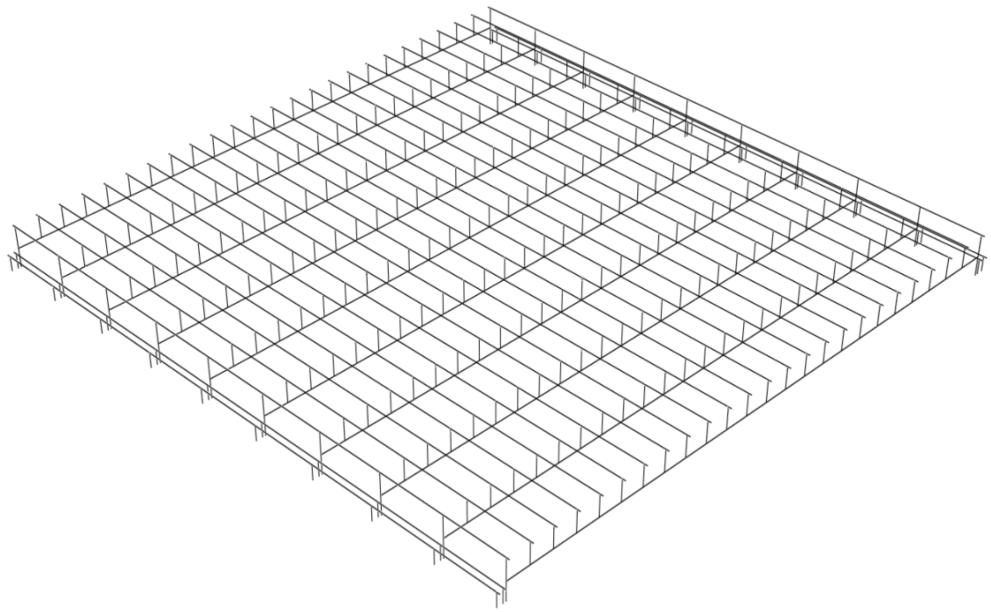

Figure 1.1 1:1 Horizontal deck model, shown as beam elements

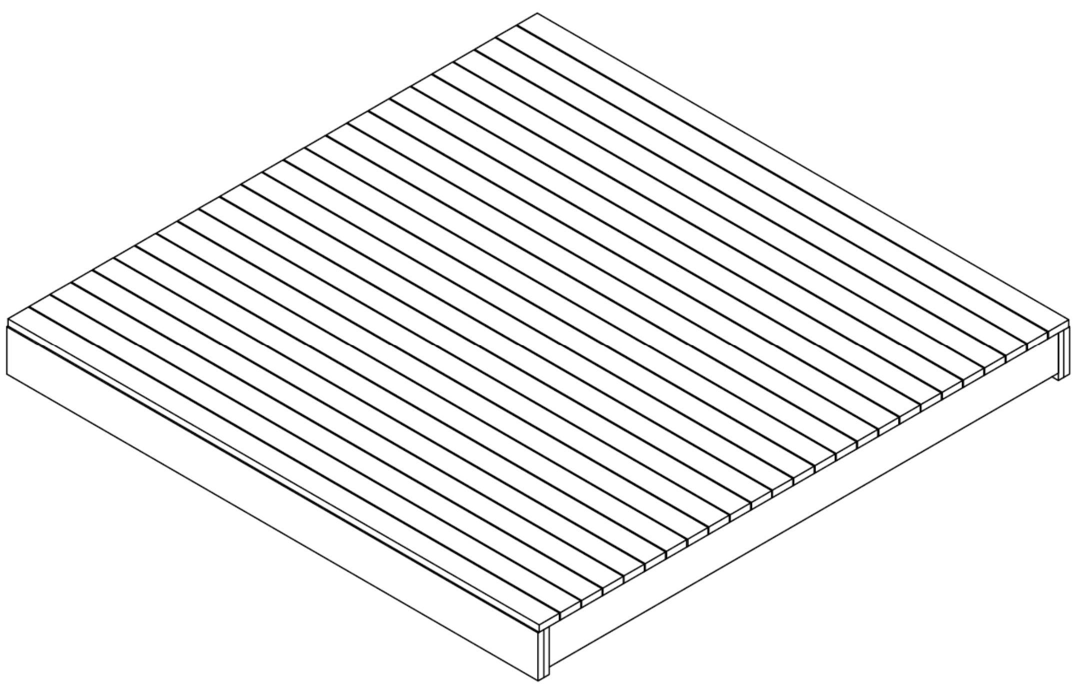

Figure 1.2 1:1 Horizontal deck model, Shown with rendered beam profiles

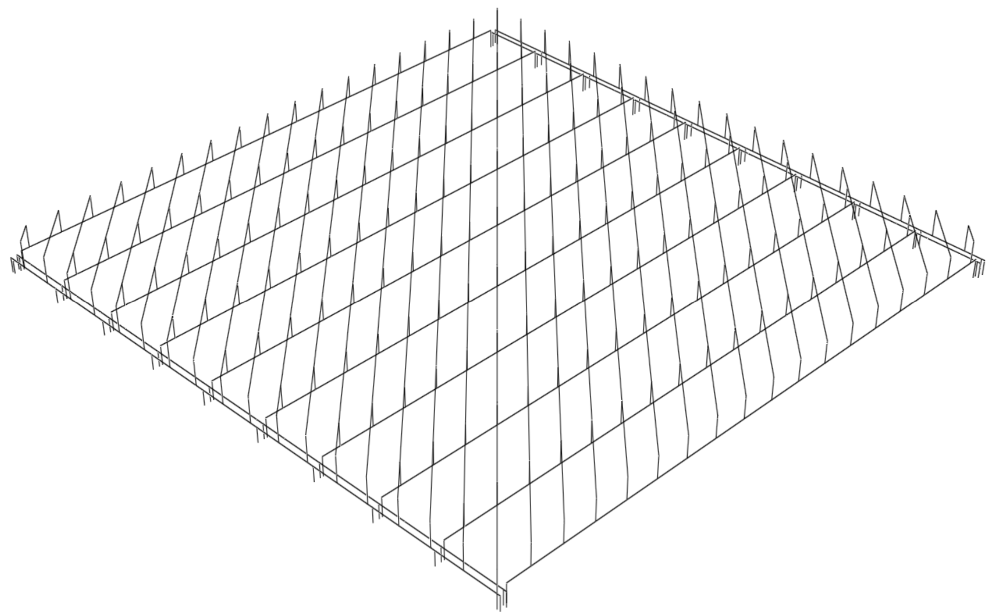

Figure 1.3 1:1 Diagonal deck model, shown as beam elements

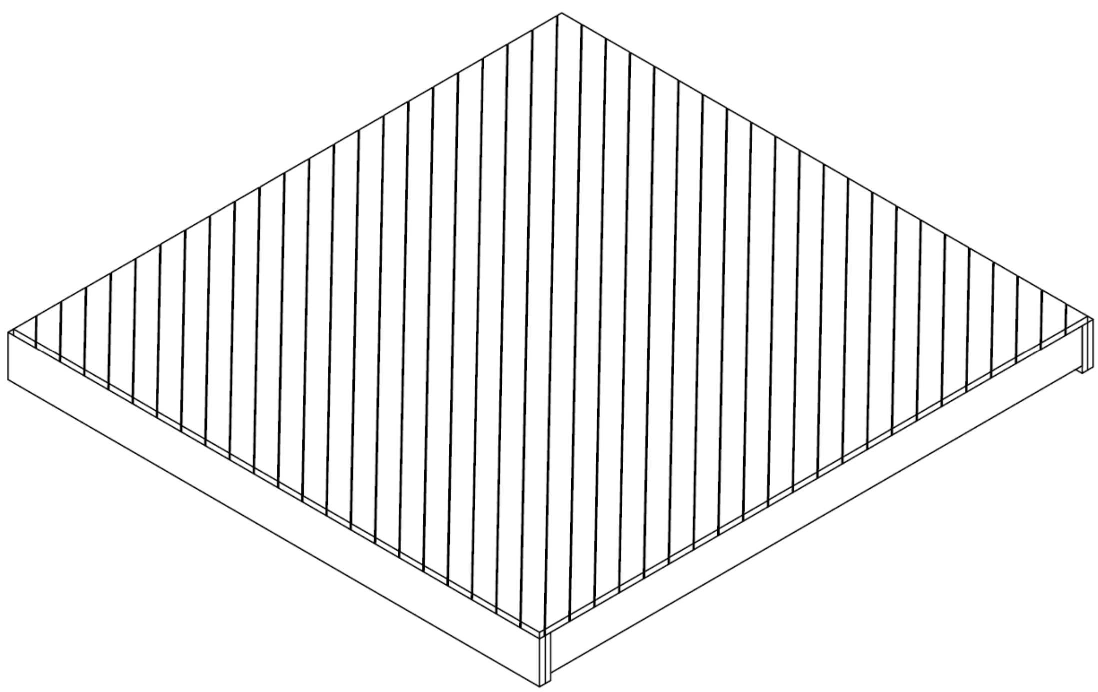

Figure 1.4 1:1 Diagonal deck model, shown with rendered beam profiles

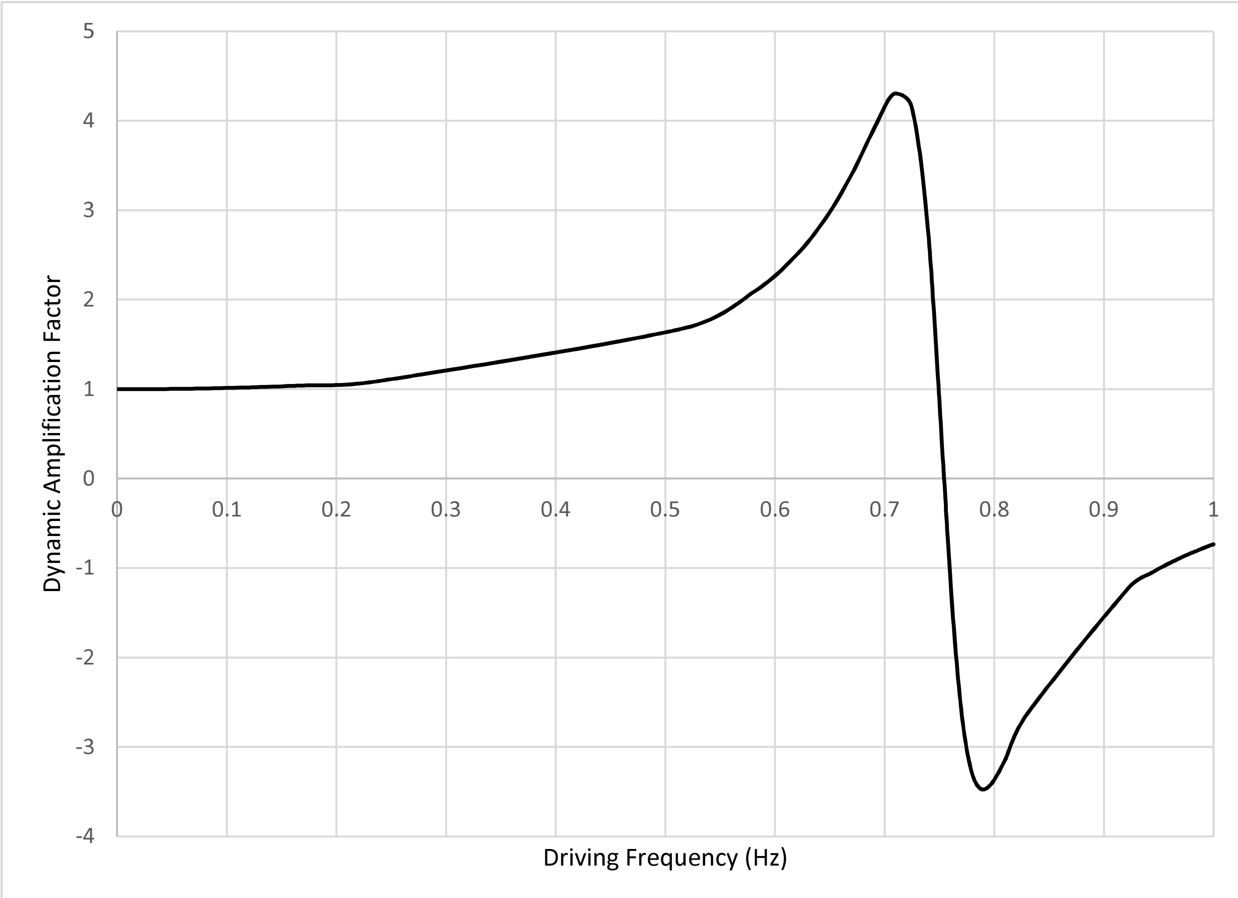

Figure 1.5 Example frequency sweep **-** horizontal boards, 1.5:1 aspect ratio, substructure stiffness = 200 lb/in. As the driving frequency approaches the natural frequency of the structure, dynamic amplification increases. A phase shift/sign change occurs directly at the natural frequency. (For more details, see Appendix A).

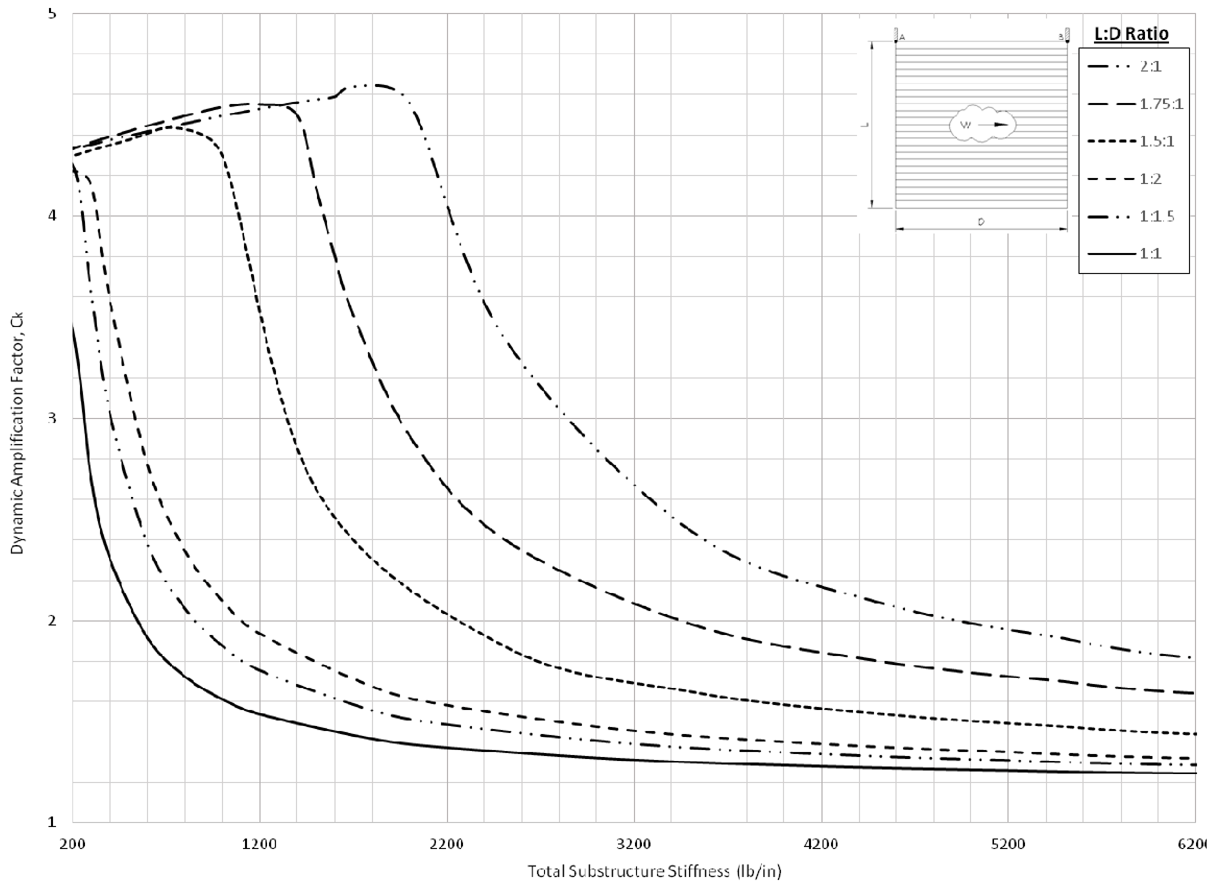

Figure 1.6 Dynamic amplification curves for horizontal deck boards at driving frequency of 1 Hz (or lower)

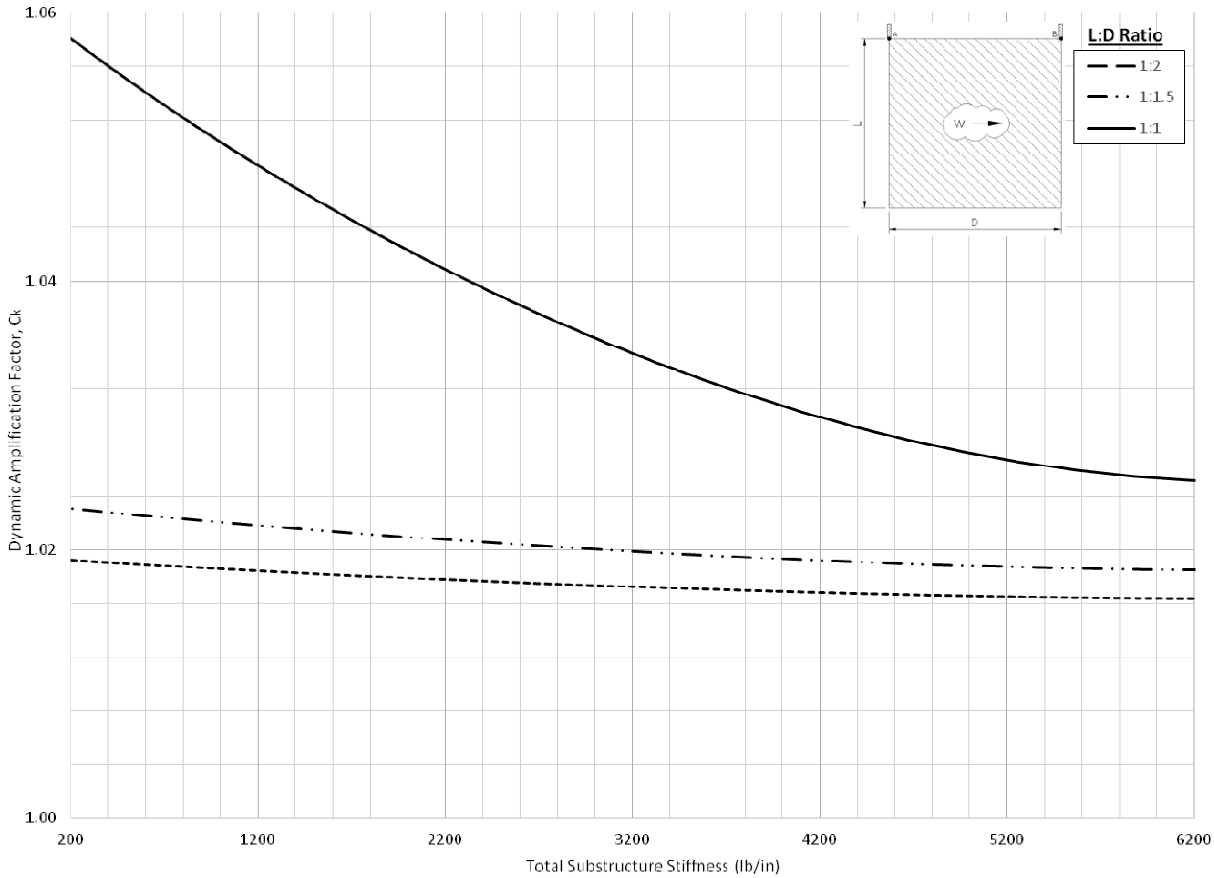

Figure 1.7 Dynamic amplification curves for diagonal deck boards at driving frequency of 1 Hz (or lower) – models along the primary structure

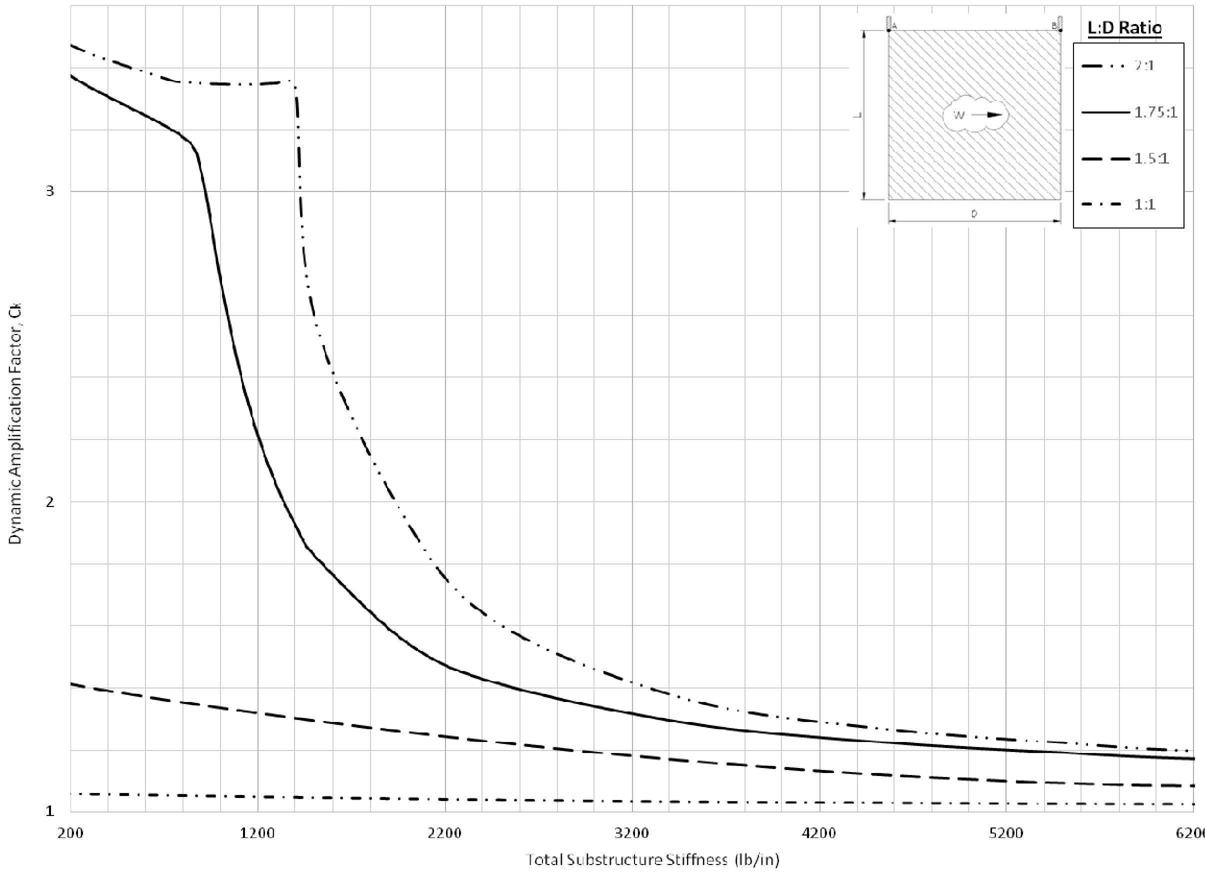

Figure 1.8 Dynamic amplification curves for diagonal deck board at driving frequency of 1 Hz (or lower) – models away from the primary structure

CHAPTER 2

PROPOSED DESIGN METHODOLOGY FOR OUTDOOR DECKS SUBJECT TO DYNAMIC LATERAL OCCUPANCY LOADS

2.1 Introduction

Each year there are numerous exterior deck failures, often occurring suddenly, resulting in personal injuries and occasionally, even deaths. While factors such as decayed members and corroded connections can increase the probability of a collapse, deck failures are usually the result of either inadequate guardrails or insufficient connections between the deck ledger and the side of the building (Carradine et al. 2007; Carradine et al. 2008). Currently in the US it is estimated that there are over 40 million decks more than 20 years old (Shutt 2011). If we consider the millions of newer decks in existence, with more of them being built every day, residential deck safety is clearly important.

Current codes require a deck to be positively anchored to the primary structure and designed for both vertical and lateral loads (ICC 2012a; 2012b). Controlling lateral loads are typically a result of occupancy and load amplification from deck movement. The development of design curves for aiding designers in determining the amplification factor for a wide range of deck constructions is discussed in chapter 1. Designers and deck builders need an efficient and straightforward way to determine dynamic occupant loads and apply them to determine subsequent structure reactions. It is not practical for design professionals to invest the time and money to develop dynamic finite element models to design decks. A simplified design procedure for determining reaction forces by examining compatibility of deflection between the diaphragm and the substructure is introduced and discussed in this chapter.

2.2 Objective

The objective of this study was to develop a simplified lateral design method for decks that could be used by design professionals and possibly to develop prescriptive designs.

2.3 Literature Review

2.3.1 Diaphragm Stiffness

Table 4.3D of the 2008 AWC *Special Design Provisions for Wind and Seismic (SDPWS)* lists the allowable design values for wood-framed shear walls. An outdoor deck is essentially a shear wall oriented in the horizontal plane. For horizontal boards, diaphragm stiffness is 1500 lb/in and nominal unit shear is 140 lb/ ft. Diagonal boards have a diaphragm stiffness of 6000 lb/in and nominal unit shear of 840 lb/ft (AWC 2008). Thus, a diaphragm sheathed with diagonal boards is 4x stiffer and 6x stronger. It should be noted that Section 4.3.3 of SDPWS states that the tabulated nominal unit shear capacity must be divided by the ASD reduction of 2.0. Therefore, the ASD allowable unit shear capacity is 70 lb/ft for horizontal boards and 420 lb/ft for diagonal boards.

The values in Table 4.3D of SDPWS originate from a document published by the Forest Products Laboratory (Trayer 1956). In this study, multiple shear walls were tested to determine rigidity and strength, including walls sheathed with both horizontal and diagonal boards. It was determined that the reaction couple formed by each pair of board fasteners was the main source of diaphragm rigidity (Trayer 1956).

Changing the fastener type/stiffness greatly affects the overall diaphragm stiffness. This held true for the finite element models reported in chapter 1. The stiffness of the springs used to connect the deck boards to the joists controlled the behavior of the entire model.

2.3.2 Composite Action

When a lateral occupancy traction load is applied to a deck, it is first applied to the deck diaphragm. The deck diaphragm resists the lateral load and is tied into the primary structure through the ledger connection and any hold-downs (if present). In addition, the deck substructure also resists lateral loads. When determining the relative contributions of the deck diaphragm and substructure, compatibility of displacements must be maintained. The substructure cannot deflect farther than the diaphragm will allow, and the deflection is limited by substructure stiffness. Lateral diaphragm deflection must be equal to substructure lateral deflection.

Deck diaphragms consist of deck boards, joists, and ledgers. Frames consist of posts, girders, joists and possibly knee bracing. In the finite element models of chapter 1, the substructure posts are represented by springs. These springs provide the additional resistance to deflection of the diaphragm just as timber posts would provide for a real deck configuration. As posts increase in stiffness, they carry a bigger portion of the load. Stiffness can be increased by adding knee braces, additional posts, or selecting a larger cross section.

Post stiffness is derived statically using formulas for cantilevered columns commonly found in beam tables. However, stiffness greatly depends on the base connection of the post. Fixed or embedded posts have greater stiffness and capacity than a surface pinned column.

2.4 Design Method Development

2.4.1 Substructure Reaction Equations

In chapter 1, design curves were developed to aid designers in determining the dynamic amplification factors for a wide range of deck constructions. It is not practical for design professionals to invest the time and money to develop dynamic finite element models to design decks. A simplified method is needed so that designers and deck builders can efficiently determine dynamic occupant loads and apply them to calculate appropriate reaction forces. This is accomplished by examining compatibility of deflection between the diaphragm and the substructure. As discussed previously in the literature review, the substructure and the diaphragm are connected and therefore must have equivalent displacements. The difference lies in the stiffness of each individual component. Stiffness attracts load, so as the substructure stiffness increases it carries more load and alleviates forces in the diaphragm.

For simplification purposes, a deck can be considered to behave like a shear beam. The structural analog of a cantilevered shear beam propped with spring supports represents a deck attached to the building and supported by posts (Figures 2.1-2.3). Stiffness becomes a function of aspect ratio and moment arm, the distance away from the primary structure. For further details, see Appendix D.

Let us again consider from chapter 1 the example of a 1:1, 12 ft. x 12 ft. deck with horizontal deck board, supported by 8 ft tall 6x6 No. 2 Hem-Fir posts, each with a single 2x4 knee brace. It was determined in chapter 1 that its configuration has a substructure stiffness of 800 lb/in, a dynamic amplification factor of 1.7, and a lateral occupancy design load of 6.8 psf. With this information, a simple ratio of stiffness based on compatibility can be used to determine substructure reaction force: The equation for the case of supports and the end of deck is as follows:

<u>For decks with supports at the end (Figures 2.1, 2.4):</u>

$$P_f = \frac{qL}{2} * \left[\frac{K}{(C + K)}\right]$$

Where:

$$P_f = Reaction\ force\ of\ substructure\ (lb)$$

$$\begin{aligned} q &= w * L = \ Traction\ line\ load\ on\ the\ deck\ (lb/ft) \\ L &= Length\ away\ from\ the\ house\ (ft) \\ D &= Length\ along\ the\ house\ (ft) \\ K &= Substructure\ stiffness\ (lb/in) \\ G_a &= Apparent\ shear\ modulus\ of\ diaphragm\ (lb/in), AWC\ SDPWS\ 2008 \\ C &= G_a * (D/L\ Ratio) = \ Diaphragm\ stiffness\ (lb/in) \end{aligned}$$

<u>For the example problem:</u>

$w = lateral\ occupancy\ design\ load = 6.8\ psf$
$q = (6.8\ psf) * (12\ ft) = 82\ lb/ft$
$L = 12\ ft$
$D = 12\ ft$
$K = 800\ lb/in$
$G_a = 1500\ lb/in$
$C = (1500\ lb/in) * (12\ ft/12\ ft) = 1500\ lb/in$

$$P_f = \frac{(82\ lb/ft) * (12\ ft)}{2} * \left[\frac{(800\ lb/in)}{(1500\ lb/in) + (800\ lb/in)}\right] = \mathbf{171\ lb}$$

Now that the substructure reaction is found, it is just a matter of static equilibrium to determine the reaction forces at the ledger. This example problem yields a hold-down force of 319 lbs at each corner and a unit shear of 67 lb/ft along the ledger.

$$B_y = \frac{\left(-P_f * L\right) + \left[w * L * D * \left(\frac{L}{2}\right)\right]}{D}$$

$$B_y = \frac{[(-171\ lb) * (12\ ft)] + \left[(6.8\ psf) * (12\ ft) * (12\ ft) * \left(\frac{12\ ft}{2}\right)\right]}{(12\ ft)} = \mathbf{319\ lb}$$

$$A_y = B_y = \mathbf{319\ lb}$$

$$v_x = \frac{\left((w * L * D) - P_f\right)}{D} = \frac{\left([(6.8\ psf) * (12\ ft) * (12\ ft)] - (171\ lb)\right)}{(12\ ft)} = \mathbf{67\ lb/ft}$$

The final step is to compare this unit shear to half the nominal value published in Table 4.3D of the American Wood Council *Special Design Provisions for Wind and Seismic* (AWC 2008). For horizontal deck boards, this value is 70 lb/ft. Since 67 lb/ft is less than 70 lb/ft, the diaphragm is able to safely carry that unit shear. (For a complete example design problem, see Appendix C). Figure 2.8 is a flowchart that graphically guides designers through the different steps of designing for lateral loads due to occupancy.

For aspect ratios extending away from the primary structure, additional supports are needed to brace against the increased moment arm. For 1.5:1 and 1.75:1 aspect ratios, a second row of supports are added (Figures 2.2, 2.5). For 2:1 aspect ratios, a row of supports at third points becomes necessary (Figure 2.3, 2.6). For the derivations of these reaction equations, see Appendix D. The equations for these scenarios are as follows:

<u>For decks with supports at end and midspan (Figures 2.2, 2.5):</u>

$$P_{f1} = \frac{KqL * (3C + K)}{2K^2 + 12CK + 8C^2}$$

$$P_{f2} = \frac{KqL * (8C + K)}{4K^2 + 24CK + 16C^2}$$

For decks with supports at third points (Figure 2.3, 2.6):

$$P_{f1} = \frac{KqL * (45C^2 + 24CK + 2K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}$$

$$P_{f2} = \frac{KqL * (72C^2 + 27CK + 2K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}$$

$$P_{f3} = \frac{KqL * (81C^2 + 18CK + K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}$$

The simplified hand method is compared with the finite element modeling predictions in Tables 2.2-2.7. The substructure stiffnesses listed in these tables represent typical post configurations a designer would use (also found in Table 2.1). This allows a designer to quickly look up the minimum substructure needed to meet shear capacity demands. Substructure stiffnesses, amplification factors, overturning forces, and unit shear checks for each of the modeled aspect ratios are provided in Tables 2.8–2.23. Tables 2.8-2.15 correspond to decks with horizontal boards, while Tables 2.16-2.23 are for diagonal deck boards.

The farther away from the primary structure, the more support a deck needs in order to pass the unit shear check. As the substructure stiffness increases, the posts attract a larger share of the load (Table 2.4 and 2.7). Unit shear decreases because more load is handled by the substructure (Tables 2.3 and 2.6). This reduces the load demand on the diaphragm and consequently the forces on the joist hangers (Tables 2.2 and 2.5).

Looking at Tables 2.8-2.23, a few interesting observations can be made. For one, it is clear that decks constructed with horizontal boards require higher substructure stiffnesses before they are able to pass the unit shear check (Tables 2.8-2.15). On the other hand, decks with diagonal boards easily pass the unit shear check, regardless of substructure stiffness (Tables 2.16-2.23). As the length away from the primary structure, L, increases relative to the length along the structure, D, the differences between the model results and the hand calculations increase (Tables 2.2-2.7). This is due to assumptions made when simplifying the decks for hand calculations. With little to no substructure stiffness, the simplified procedure treats the deck like a cantilevered beam, fixed at the building and pinned at each post. As substructure stiffness increases, the deck becomes more like a simple beam, restrained at both ends. The simplified hand calculations only account for reactions in the horizontal plane of the lateral load. The 3D models include reactions and displacements in all 3 coordinate planes, but compared to the reactions in the horizontal plane of the lateral load, the reaction forces in the other 2 coordinate planes are negligible.

Furthermore, substructure stiffness is high when posts are fixed (embedded) into the ground. Stiffness is reduced when posts are only surface mounted (pinned) the ground. In reality, each post connection is somewhere in-between fixed and pinned, so assuming one or the other is a matter of engineering judgment.

Another interesting aspect of Table 2.5 is the difference between the model and hand calculated anchor forces for diagonal deck boards. As length away from the primary structure increases, the discrepancy between values becomes even greater. This is because after the 1:1 aspect ratio, the diagonal deck boards begin to span only from joist to joist (Figure 2.7). While the models account for this load path, the simplified hand method does not. The hand method treats the deck boards as one homogenous diaphragm, the entire load going directly into the ledger.

Similarly, the difference between the maximum hanger force and the summation of all the hangers along the ledger decreases with distance away from the primary structure. The maximum hanger force occurs in the outermost joist hangers. As shown in Table 2.5, the difference decreases until the two columns are identical. With increased aspect ratio away from the primary structure, more diagonal deck boards begin to span purely joist to joist. The load path puts the majority of the applied load into the outermost joints, which in turn apply the load to the outermost joist hangers. The inner joist hangers carry little to no portion of the lateral load. Likewise, when the aspect ratio increases along the length of the building, the inner joist hangers receive a larger share of the load and the difference between the maximum hanger force and the summation increases.

2.4.2 Aspect Ratio - Sensitivity Analysis

While analyzing the model results and developing the design curves, the question was raised as to whether a 1:1 deck of different dimensions would have the same response as the 1:1, 12’x12’ deck that was the basis for these tests. It was theorized that a 1:1 deck with different dimensions would in fact have a different response due to a different moment arm (distance away from the primary structure). To test this hypothesis, models of a 1:1, 16’x16’ deck with both horizontal and diagonal deck boards were generated (Tables 2.26, 2.28, 2.29). When compared with the results of the 12’x12’ deck (Table 2.24), it becomes apparent that two decks with the same aspect ratio can yield different results. The distance of the deck centroid away from the primary structure controls the response of the deck. An additional 1.5:1, 24’x16’ deck was created (Table 2.27) and compared to the 1.5:1, 18’x12’ deck (Table 2.25). The results were similar. Even though they were both 1.5:1 aspect ratios, the 24’x16’ deck has higher amplification factors, being farther away from the primary structure than the 18’x12’ deck.

2.5 Summary and Conclusions

Designers need an efficient and straightforward way to determine dynamic occupant loads and complete a lateral design of decks. It is not likely that designers would invest time and money into developing dynamic finite elements models for every deck they design. Thus, a simplified design procedure for determining reaction forces was created by examining compatibility of deflection between the diaphragm and the substructure.

Equations were formulated that allow a designer to easily determine useful information such as post reactions, overturning forces, and unit shear for a given aspect ratio. Assumptions are made when simplifying the procedure to be calculated by hand, but the results of these quick hand checks allow designers to consider lateral loads due to occupancy on their decks without running costly computer models they would otherwise need to acquire the same information. As with any design procedure, engineers must use their best judgment. Both the dynamic amplification curves and the simplified procedure are meant to help a designer develop better, stronger, and safer decks.

This chapter further illustrates that dynamic amplification of lateral occupancy loads on an outdoor deck is an issue that cannot be ignored. When developing the amplification factor design curves, the lateral traction load applied to the finite element models was based solely on occupants swaying side to side. It would be interesting for further research to consider additional live gravity loads, such as furniture, planters and hot tub.

Future research needs to further investigate decks with equal aspect ratios but with different dimensions. Either new design curves should be developed, or a method of plotting the current curves to account for all variations of particular aspect ratios should be established.

2.6 References

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2.7 Tables

6x6 Posts	Substructure Description	Total Substructure Stiffness (lb/in)	6x6 Posts	Substructure Description	Total Substructure Stiffness (lb/in)
Embedded Posts 2 Total	No Substructure	0	Pinned Posts 2 Total	No Substructure	0
	10 ft posts, no bracing	291		10 ft posts, no bracing	0
	10 ft posts, 1 brace each	452		10 ft posts, 1 brace each	74
	10 ft posts, 2 braces each	588		10 ft posts, 2 braces each	131
	8 ft posts, no bracing	569		8 ft posts, no bracing	0
	8 ft posts, 1 brace each	816		8 ft posts, 1 brace each	121
	8 ft posts, 2 braces each	1036		8 ft posts, 2 braces each	221
	6 ft posts, no bracing	1348		6 ft posts, no bracing	0
	6 ft posts, 1 brace each	1753		6 ft posts, 1 brace each	223
	6 ft posts, 2 braces each	2130		6 ft posts, 2 braces each	424
Embedded Posts 4 Total	No Substructure	0	Pinned Posts 4 Total	No Substructure	0
	10 ft posts, no bracing	583		10 ft posts, no bracing	0
	10 ft posts, 1 brace each	904		10 ft posts, 1 brace each	148
	10 ft posts, 2 braces each	1176		10 ft posts, 2 braces each	262
	8 ft posts, no bracing	1138		8 ft posts, no bracing	0
	8 ft posts, 1 brace each	1632		8 ft posts, 1 brace each	242
	8 ft posts, 2 braces each	2073		8 ft posts, 2 braces each	442
	6 ft posts, no bracing	2697		6 ft posts, no bracing	0
	6 ft posts, 1 brace each	3506		6 ft posts, 1 brace each	446
	6 ft posts, 2 braces each	4260		6 ft posts, 2 braces each	848
Embedded Posts 6 Total	No Substructure	0	Pinned Posts 6 Total	No Substructure	0
	10 ft posts, no bracing	1748		10 ft posts, no bracing	0
	10 ft posts, 1 brace each	2713		10 ft posts, 1 brace each	222
	10 ft posts, 2 braces each	3529		10 ft posts, 2 braces each	393
	8 ft posts, no bracing	3413		8 ft posts, no bracing	0
	8 ft posts, 1 brace each	4896		8 ft posts, 1 brace each	363
	8 ft posts, 2 braces each	6218		8 ft posts, 2 braces each	663
	6 ft posts, no bracing	9081		6 ft posts, no bracing	0
	6 ft posts, 1 brace each	10519		6 ft posts, 1 brace each	669
	6 ft posts, 2 braces each	12779		6 ft posts, 2 braces each	1272

Table 2.1 Total substructure stiffness values for common substructure configurations

	Anchor Forces				
	Aspect Ratio (L:D)	Amplification Factor	FEM Maximum Hanger Force (lb)	FEM Σ of Hangers (lb)	Tie Down (Hand Calcs) (lb)
200 lb/in	1:1	**3.44**	649	742	812
	1:1.5	**4.26**	971	1159	1117
	1:2	**4.22**	974	1252	1149
	1.5:1	**4.30**	1870	2096	1604
	1.75:1	**4.33**	2391	2728	1897
	2:1	**4.33**	3114	3663	
1000 lb/in	1:1	**1.61**	131	154	220
	1:1.5	**1.88**	224	266	363
	1:2	**2.10**	271	353	469
	1.5:1	**4.30**	755	882	559
	1.75:1	**4.54**	1000	1126	609
	2:1	**4.50**	1310	1513	
1800 lb/in	1:1	**1.42**	72	88	136
	1:1.5	**1.56**	125	148	239
	1:2	**1.67**	148	196	317
	1.5:1	**2.42**	263	309	183
	1.75:1	**3.31**	450	497	252
	2:1	**4.61**	835	947	
3500 lb/in	1:1	**1.30**	35	46	77
	1:1.5	**1.38**	66	77	146
	1:2	**1.43**	74	101	206
	1.5:1	**1.65**	96	114	64
	1.75:1	**1.99**	148	158	77
	2:1	**2.45**	243	267	
6500 lb/in	1:1	**1.24**	19	25	44
	1:1.5	**1.28**	36	41	89
	1:2	**1.32**	38	55	132
	1.5:1	**1.43**	45	55	29
	1.75:1	**1.64**	69	73	33
	2:1	**1.80**	100	107	

Table 2.2 *Horizontal boards;* Comparison of anchor forces, FEM vs. simplified method

	Unit Shear					
	Aspect Ratio (D:L)	Amplification Factor	(FEM) Shear in Ledger (lb)	(Hand) Shear in Ledger (lb)	Shear Check (FEM) (lb)	Shear Check (Hand) (lb)
200 lb/in	1:1	**3.44**	140	150	**NO GOOD**	**NO GOOD**
	1:1.5	**4.26**	181	195	**NO GOOD**	**NO GOOD**
	1:2	**4.22**	184	197	**NO GOOD**	**NO GOOD**
	1.5:1	**4.30**	246	225	**NO GOOD**	**NO GOOD**
	1.75:1	**4.33**	280	245	**NO GOOD**	**NO GOOD**
	2:1	**4.33**	314		**NO GOOD**	**NO GOOD**
1000 lb/in	1:1	**1.61**	50	57	**OKAY**	**OKAY**
	1:1.5	**1.88**	63	75	**OKAY**	**NO GOOD**
	1:2	**2.10**	74	89	**NO GOOD**	**NO GOOD**
	1.5:1	**4.30**	168	143	**NO GOOD**	**NO GOOD**
	1.75:1	**4.54**	197	161	**NO GOOD**	**NO GOOD**
	2:1	**4.50**	208		**NO GOOD**	**NO GOOD**
1800 lb/in	1:1	**1.42**	41	45	**OKAY**	**OKAY**
	1:1.5	**1.56**	47	57	**OKAY**	**OKAY**
	1:2	**1.67**	53	67	**OKAY**	**OKAY**
	1.5:1	**2.42**	82	68	**NO GOOD**	**OKAY**
	1.75:1	**3.31**	124	101	**NO GOOD**	**NO GOOD**
	2:1	**4.61**	180		**NO GOOD**	**NO GOOD**
3500 lb/in	1:1	**1.30**	35	38	**OKAY**	**OKAY**
	1:1.5	**1.38**	38	45	**OKAY**	**OKAY**
	1:2	**1.43**	41	52	**OKAY**	**OKAY**
	1.5:1	**1.65**	48	40	**OKAY**	**OKAY**
	1.75:1	**1.99**	65	53	**OKAY**	**OKAY**
	2:1	**2.45**	80		**NO GOOD**	**NO GOOD**
6500 lb/in	1:1	**1.24**	32	33	**OKAY**	**OKAY**
	1:1.5	**1.28**	34	38	**OKAY**	**OKAY**
	1:2	**1.32**	36	43	**OKAY**	**OKAY**
	1.5:1	**1.43**	38	31	**OKAY**	**OKAY**
	1.75:1	**1.64**	49	40	**OKAY**	**OKAY**
	2:1	**1.80**	52		**OKAY**	**OKAY**

Table 2.3 *Horizontal boards;* Comparison of unit shears, FEM vs. simplified method

	Post (Reaction) Forces							
	Aspect Ratio (D:L)	Amplification Factor	(FEM) Post 1 Force (lb)	(Hand) Post 1 Force (lb)	(FEM) Post 2 Force (lb)	(Hand) Post 2 Force (lb)	(FEM) Post 3 Force (lb)	(Hand) Post 3 Force (lb)
200 lb/in	1:1	**3.44**	305	179	-	-	-	-
	1:1.5	**4.26**	432	163	-	-	-	-
	1:2	**4.22**	456	132	-	-	-	-
	1.5:1	**4.30**	328	461	436	588	-	-
	1.75:1	**4.33**	433	657	566	771	-	-
	2:1	**4.33**		272		442		498
1000 lb/in	1:1	**1.61**	317	244	-	-	-	-
	1:1.5	**1.88**	499	265	-	-	-	-
	1:2	**2.10**	648	270	-	-	-	-
	1.5:1	**4.30**	775	1027	926	972	-	-
	1.75:1	**4.54**	1021	1404	1178	1237	-	-
	2:1	**4.50**		666		976		1043
1800 lb/in	1:1	**1.42**	328	271	-	-	-	-
	1:1.5	**1.56**	503	314	-	-	-	-
	1:2	**1.67**	651	329	-	-	-	-
	1.5:1	**2.42**	526	696	589	574	-	-
	1.75:1	**3.31**	886	1205	959	923	-	-
	2:1	**4.61**		835		1149		1189
3500 lb/in	1:1	**1.30**	331	298	-	-	-	-
	1:1.5	**1.38**	515	375	-	-	-	-
	1:2	**1.43**	658	415	-	-	-	-
	1.5:1	**1.65**	416	555	429	392	-	-
	1.75:1	**1.99**	610	823	599	545	-	-
	2:1	**2.45**		525		668		666
6500 lb/in	1:1	**1.24**	336	314	-	-	-	-
	1:1.5	**1.28**	517	422	-	-	-	-
	1:2	**1.32**	673	494	-	-	-	-
	1.5:1	**1.43**	394	533	379	333	-	-
	1.75:1	**1.64**	547	735	501	438	-	-
	2:1	**1.80**		434		514		499

Table 2.4 *Horizontal boards;* Comparison of post reactions, FEM vs. simplified method

	Anchor Forces				
	Aspect Ratio (L:D)	Amplification Factor	FEM Maximum Hanger Force (lb)	FEM Σ of Hangers (lb)	Tie Down (Hand Calcs) (lb)
200 lb/in	1:1	**3.44**	320	382	299
	1:1.5	**4.26**	133	504	294
	1:2	**4.22**	91	493	293
	1.5:1	**4.30**	3136	3179	2101
	1.75:1	**4.33**	5115	5115	2408
	2:1	**4.33**	6739	6739	
1000 lb/in	1:1	**1.61**	284	342	278
	1:1.5	**1.88**	129	492	289
	1:2	**2.10**	90	485	289
	1.5:1	**4.30**	2228	2244	1030
	1.75:1	**4.54**	3529	3529	966
	2:1	**4.50**	4513	4513	
1800 lb/in	1:1	**1.42**	254	309	259
	1:1.5	**1.56**	125	480	285
	1:2	**1.67**	88	478	286
	1.5:1	**2.42**	1034	1039	375
	1.75:1	**3.31**	2098	2098	422
	2:1	**4.61**	3781	3781	
3500 lb/in	1:1	**1.30**	209	258	226
	1:1.5	**1.38**	117	456	276
	1:2	**1.43**	85	463	280
	1.5:1	**1.65**	548	549	142
	1.75:1	**1.99**	1588	1588	132
	2:1	**2.45**	1588	1588	
6500 lb/in	1:1	**1.24**	154	199	184
	1:1.5	**1.28**	106	421	262
	1:2	**1.32**	80	439	269
	1.5:1	**1.43**	370	371	67
	1.75:1	**1.64**	995	995	58
	2:1	**1.80**	947	947	

Table 2.5 *Diagonal boards;* Comparison of anchor forces, FEM vs. simplified method

	Unit Shear					
	Aspect Ratio (D:L)	Amplification Factor	(FEM) Shear in Ledger (lb)	(Hand) Shear in Ledger (lb)	Shear Check (FEM) (lb)	Shear Check (Hand) (lb)
200 lb/in	1:1	**3.44**	50	50	**OKAY**	**OKAY**
	1:1.5	**4.26**	49	49	**OKAY**	**OKAY**
	1:2	**4.22**	49	49	**OKAY**	**OKAY**
	1.5:1	**4.30**	285	261	**OKAY**	**OKAY**
	1.75:1	**4.33**	318	277	**OKAY**	**OKAY**
	2:1	**4.33**	349		**OKAY**	**OKAY**
1000 lb/in	1:1	**1.61**	47	48	**OKAY**	**OKAY**
	1:1.5	**1.88**	48	49	**OKAY**	**OKAY**
	1:2	**2.10**	49	49	**OKAY**	**OKAY**
	1.5:1	**4.30**	232	181	**OKAY**	**OKAY**
	1.75:1	**4.54**	261	188	**OKAY**	**OKAY**
	2:1	**4.50**	272		**OKAY**	**OKAY**
1800 lb/in	1:1	**1.42**	45	47	**OKAY**	**OKAY**
	1:1.5	**1.56**	48	48	**OKAY**	**OKAY**
	1:2	**1.67**	48	48	**OKAY**	**OKAY**
	1.5:1	**2.42**	119	86	**OKAY**	**OKAY**
	1.75:1	**3.31**	173	116	**OKAY**	**OKAY**
	2:1	**4.61**	251		**OKAY**	**OKAY**
3500 lb/in	1:1	**1.30**	41	44	**OKAY**	**OKAY**
	1:1.5	**1.38**	47	48	**OKAY**	**OKAY**
	1:2	**1.43**	47	48	**OKAY**	**OKAY**
	1.5:1	**1.65**	73	48	**OKAY**	**OKAY**
	1.75:1	**1.99**	95	59	**OKAY**	**OKAY**
	2:1	**2.45**	121		**OKAY**	**OKAY**
6500 lb/in	1:1	**1.24**	37	40	**OKAY**	**OKAY**
	1:1.5	**1.28**	45	46	**OKAY**	**OKAY**
	1:2	**1.32**	46	47	**OKAY**	**OKAY**
	1.5:1	**1.43**	59	36	**OKAY**	**OKAY**
	1.75:1	**1.64**	74	43	**OKAY**	**OKAY**
	2:1	**1.80**	84		**OKAY**	**OKAY**

Table 2.6 *Diagonal Boards;* Comparison of unit shears, FEM vs. simplified method

	Post (Reaction) Forces							
	Aspect Ratio (D:L)	Amplification Factor	(FEM) Post 1 Force (lb)	(Hand) Post 1 Force (lb)	(FEM) Post 2 Force (lb)	(Hand) Post 2 Force (lb)	(FEM) Post 3 Force (lb)	(Hand) Post 3 Force (lb)
200 lb/in	1:1	**3.44**	9	6	-	-	-	-
	1:1.5	**4.26**	3	2	-	-	-	-
	1:2	**4.22**	2	2	-	-	-	-
	1.5:1	**4.30**	115	258	236	328	-	-
	1.75:1	**4.33**	187	467	387	575	-	-
	2:1	**4.33**		139		263		388
1000 lb/in	1:1	**1.61**	41	26	-	-	-	-
	1:1.5	**1.88**	15	8	-	-	-	-
	1:2	**2.10**	12	8	-	-	-	-
	1.5:1	**4.30**	288	732	699	805	-	-
	1.75:1	**4.54**	422	1163	1039	1153	-	-
	2:1	**4.50**		314		607		996
1800 lb/in	1:1	**1.42**	67	43	-	-	-	-
	1:1.5	**1.56**	27	14	-	-	-	-
	1:2	**1.67**	22	14	-	-	-	-
	1.5:1	**2.42**	184	534	515	538	-	-
	1.75:1	**3.31**	330	1042	938	907	-	-
	2:1	**4.61**		358		699		1255
3500 lb/in	1:1	**1.30**	107	74	-	-	-	-
	1:1.5	**1.38**	50	26	-	-	-	-
	1:2	**1.43**	41	27	-	-	-	-
	1.5:1	**1.65**	124	457	441	389	-	-
	1.75:1	**1.99**	185	744	673	553	-	-
	2:1	**2.45**		192		379		796
6500 lb/in	1:1	**1.24**	148	111	-	-	-	-
	1:1.5	**1.28**	84	46	-	-	-	-
	1:2	**1.32**	71	47	-	-	-	-
	1.5:1	**1.43**	92	465	447	342	-	-
	1.75:1	**1.64**	128	687	628	447	-	-
	2:1	**1.80**		134		260		669

Table 2.7 *Diagonal boards;* Comparison of post reactions, FEM vs. simplified method

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.951	**4.15**	1194	199	**NO GOOD**
		18	0.941	**4.15**	1194	199	**NO GOOD**
		24	0.938	**4.14**	1194	199	**NO GOOD**
10 ft - Outer corners, no bracing	291	12	1.119	**2.76**	675	130	**NO GOOD**
		18	1.102	**3.68**	1058	167	**NO GOOD**
		24	1.067	**4.16**	1149	171	**NO GOOD**
10 ft - Outer corners, 1 brace each	452	12	1.281	**2.20**	556	112	**NO GOOD**
		18	1.176	**2.86**	878	144	**NO GOOD**
		24	1.128	**3.37**	968	149	**NO GOOD**
10 ft - Outer corners, 2 braces each	588	12	1.355	**1.94**	457	97	**NO GOOD**
		18	1.233	**2.42**	726	124	**NO GOOD**
		24	1.177	**2.82**	816	130	**NO GOOD**
8 ft - Outer corners, no bracing	569	12	1.345	**1.97**	470	99	**NO GOOD**
		18	1.225	**2.48**	748	127	**NO GOOD**
		24	1.170	**2.89**	837	133	**NO GOOD**
8 ft - Outer corners, 1 brace each	816	12	1.461	**1.71**	289	71	**NO GOOD**
		18	1.318	**2.05**	472	90	**NO GOOD**
		24	1.250	**2.32**	560	99	**NO GOOD**
8 ft - Outer corners, 2 braces each	1036	12	1.545	**1.60**	151	50	**OKAY**
		18	1.389	**1.85**	261	63	**OKAY**
		24	1.313	**2.07**	346	73	**NO GOOD**
6 ft - Outer corners, no bracing	1348	12	1.639	**1.51**	125	46	**OKAY**
		18	1.473	**1.71**	215	56	**OKAY**
		24	1.389	**1.87**	285	65	**OKAY**
6 ft - Outer corners, 1 brace each	1753	12	1.743	**1.43**	92	42	**OKAY**
		18	1.571	**1.57**	155	48	**OKAY**
		24	1.479	**1.69**	205	54	**OKAY**
6 ft - Outer corners, 2 braces each	2130	12	1.816	**1.38**	80	40	**OKAY**
		18	1.644	**1.50**	135	46	**OKAY**
		24	1.549	**1.60**	177	51	**OKAY**

Table 2.8 *Horizontal boards, embedded posts, L = 12 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.630	**4.25**	2751	306	**NO GOOD**
10 ft - Outer corners, Midspan , no bracing	583	12	0.930	**4.40**	1515	209	**NO GOOD**
10 ft - Outer corners, Midspan , 1 brace each	904	12	1.050	**4.34**	1028	177	**NO GOOD**
10 ft - Outer corners, Midspan , 2 braces each	1176	12	1.125	**3.72**	756	149	**NO GOOD**
8 ft - Outer corners, Midspan , no bracing	1138	12	1.115	**3.85**	783	153	**NO GOOD**
8 ft - Outer corners, Midspan , 1 brace each	1632	12	1.238	**2.55**	429	100	**NO GOOD**
8 ft - Outer corners, Midspan , 2 braces each	2073	12	1.322	**2.21**	277	76	**NO GOOD**
6 ft - Outer corners, Midspan , no bracing	2697	12	1.428	**1.83**	206	64	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	3506	12	1.532	**1.69**	114	48	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	4260	12	1.601	**1.57**	99	46	**OKAY**

Table 2.9 *Horizontal boards, embedded posts, L = 18 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.545	**4.27**	3766	359	**NO GOOD**
10 ft - Outer corners, Midspan , no bracing	583	12	0.837	**4.44**	1972	240	**NO GOOD**
10 ft - Outer corners, Midspan , 1 brace each	904	12	0.944	**4.52**	1321	207	**NO GOOD**
10 ft - Outer corners, Midspan , 2 braces each	1176	12	1.109	**4.55**	988	181	**NO GOOD**
8 ft - Outer corners, Midspan , no bracing	1138	12	1.009	**4.55**	1018	184	**NO GOOD**
8 ft - Outer corners, Midspan , 1 brace each	1632	12	1.121	**3.71**	629	139	**NO GOOD**
8 ft - Outer corners, Midspan , 2 braces each	2073	12	1.198	**2.84**	531	130	**NO GOOD**
6 ft - Outer corners, Midspan , no bracing	2697	12	1.282	**2.32**	318	93	**NO GOOD**
6 ft - Outer corners, Midspan , 1 brace each	3506	12	1.370	**1.98**	158	65	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	4260	12	1.427	**1.85**	137	61	**OKAY**

Table 2.10 *Horizontal Boards, embedded Posts, L = 21 ft. from Building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.480	**4.29**	4938	412	**NO GOOD**
		16	0.478	**4.29**	4942	412	**NO GOOD**
10 ft - Third Points, no bracing	1748	12	1.026	**4.63**	984	181	**NO GOOD**
		16	0.927	**4.56**	1241	199	**NO GOOD**
10 ft - Third Points, 1 brace each	2713	12	1.166	**3.20**	582	126	**NO GOOD**
		16	1.054	**4.50**	842	161	**NO GOOD**
10 ft - Third Points, 2 braces each	3529	12	1.256	**2.44**	265	80	**NO GOOD**
		16	1.134	**3.55**	530	130	**NO GOOD**
8 ft - Third Points, no bracing	3413	12	1.244	**2.53**	301	85	**NO GOOD**
		16	1.123	**3.71**	568	134	**NO GOOD**
8 ft - Third Points, 1 brace each	4896	12	1.356	**2.02**	192	67	**OKAY**
		16	1.226	**2.64**	373	103	**NO GOOD**
8 ft - Third Points, 2 braces each	6218	12	1.424	**1.83**	122	55	**OKAY**
		16	1.291	**2.26**	221	77	**NO GOOD**
6 ft - Third Points, no bracing	9081	12	1.437	**1.80**	86	42	**OKAY**
		16	1.303	**2.20**	152	58	**OKAY**
6 ft - Third Points, 1 brace each	10519	12	1.437	**1.80**	75	37	**OKAY**
		16	1.317	**2.17**	132	50	**OKAY**
6 ft - Third Points, 2 braces each	12779	12	1.437	**1.80**	57	28	**OKAY**
		16	1.325	**2.15**	101	38	**OKAY**

Table 2.11 *Horizontal boards, embedded Posts, L = 24 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.951	**4.15**	1194	199	**NO GOOD**
		18	0.941	**4.15**	1194	199	**NO GOOD**
		24	0.938	**4.14**	1194	199	**NO GOOD**
10 ft - Outer corners, no bracing	0	12	0.951	**4.15**	1194	199	**NO GOOD**
		18	0.941	**4.15**	1194	199	**NO GOOD**
		24	0.938	**4.14**	1194	199	**NO GOOD**
10 ft - Outer corners, 1 brace each	74	12	1.013	**3.89**	1035	179	**NO GOOD**
		18	0.984	**4.18**	1143	196	**NO GOOD**
		24	0.971	**4.17**	1155	196	**NO GOOD**
10 ft - Outer corners, 2 braces each	131	12	1.061	**3.69**	927	166	**NO GOOD**
		18	1.016	**4.22**	1108	194	**NO GOOD**
		24	0.998	**4.19**	1126	195	**NO GOOD**
8 ft - Outer corners, no bracing	0	12	0.951	**4.15**	1194	199	**NO GOOD**
		18	0.941	**4.15**	1194	199	**NO GOOD**
		24	0.938	**4.14**	1194	199	**NO GOOD**
8 ft - Outer corners, 1 brace each	121	12	1.052	**3.72**	945	168	**NO GOOD**
		18	1.011	**4.21**	1114	194	**NO GOOD**
		24	0.993	**4.19**	1131	195	**NO GOOD**
8 ft - Outer corners, 2 braces each	221	12	1.133	**3.29**	726	138	**NO GOOD**
		18	1.067	**4.12**	1136	178	**NO GOOD**
		24	1.038	**4.20**	1228	181	**NO GOOD**
6 ft - Outer corners, no bracing	0	12	0.951	**4.15**	1194	199	**NO GOOD**
		18	0.941	**4.15**	1194	199	**NO GOOD**
		24	0.938	**4.14**	1194	199	**NO GOOD**
6 ft - Outer corners, 1 brace each	223	12	1.135	**3.27**	725	138	**NO GOOD**
		18	1.068	**4.11**	1134	177	**NO GOOD**
		24	1.039	**4.20**	1226	181	**NO GOOD**
6 ft - Outer corners, 2 braces each	424	12	1.265	**2.26**	577	115	**NO GOOD**
		18	1.164	**2.94**	909	148	**NO GOOD**
		24	1.118	**3.48**	1000	153	**NO GOOD**

Table 2.12 *Horizontal boards, pinned posts, L = 12 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.630	**4.25**	2751	306	**NO GOOD**
10 ft - Outer corners, Midspan , no bracing	0	12	0.630	**4.25**	2751	306	**NO GOOD**
10 ft - Outer corners, Midspan , 1 brace each	148	12	0.721	**4.29**	2206	277	**NO GOOD**
10 ft - Outer corners, Midspan , 2 braces each	262	12	0.783	**4.32**	2002	240	**NO GOOD**
8 ft - Outer corners, Midspan , no bracing	0	12	0.630	**4.25**	2751	306	**NO GOOD**
8 ft - Outer corners, Midspan , 1 brace each	242	12	0.773	**4.31**	2032	242	**NO GOOD**
8 ft - Outer corners, Midspan , 2 braces each	442	12	0.870	**4.36**	1729	222	**NO GOOD**
6 ft - Outer corners, Midspan , no bracing	0	12	0.630	**4.25**	2751	306	**NO GOOD**
6 ft - Outer corners, Midspan , 1 brace each	446	12	0.872	**4.36**	1723	222	**NO GOOD**
6 ft - Outer corners, Midspan , 2 braces each	848	12	1.027	**4.38**	1112	183	**NO GOOD**

Table 2.13 *Horizontal boards, pinned posts, L = 18 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.545	**4.27**	3766	359	**NO GOOD**
10 ft - Outer corners, Midspan , no bracing	0	12	0.545	**4.27**	3766	359	**NO GOOD**
10 ft - Outer corners, Midspan , 1 brace each	148	12	0.642	**4.32**	2924	321	**NO GOOD**
10 ft - Outer corners, Midspan , 2 braces each	262	12	0.697	**4.35**	2623	274	**NO GOOD**
8 ft - Outer corners, Midspan , no bracing	0	12	0.545	**4.27**	3766	359	**NO GOOD**
8 ft - Outer corners, Midspan , 1 brace each	242	12	0.687	**4.35**	2663	276	**NO GOOD**
8 ft - Outer corners, Midspan , 2 braces each	442	12	0.780	**4.40**	2258	255	**NO GOOD**
6 ft - Outer corners, Midspan , no bracing	0	12	0.545	**4.27**	3766	359	**NO GOOD**
6 ft - Outer corners, Midspan , 1 brace each	446	12	0.782	**4.40**	2249	254	**NO GOOD**
6 ft - Outer corners, Midspan , 2 braces each	848	12	0.927	**4.50**	1434	213	**NO GOOD**

Table 2.14 *Horizontal boards, pinned posts, L = 21 ft. from building.* Substructure stiffnesses, Compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.480	**4.29**	4938	412	**NO GOOD**
		16	0.478	**4.29**	4942	412	**NO GOOD**
10 ft - Third Points, no bracing	0	12	0.480	**4.29**	4938	412	**NO GOOD**
		16	0.478	**4.29**	4942	412	**NO GOOD**
10 ft - Third Points, 1 brace each	222	12	0.597	**4.34**	3604	311	**NO GOOD**
		16	0.568	**4.33**	3900	332	**NO GOOD**
10 ft - Third Points, 2 braces each	393	12	0.670	**4.37**	3144	289	**NO GOOD**
		16	0.625	**4.36**	3447	309	**NO GOOD**
8 ft - Third Points, no bracing	0	12	0.480	**4.29**	4938	412	**NO GOOD**
		16	0.478	**4.29**	4942	412	**NO GOOD**
8 ft - Third Points, 1 brace each	363	12	0.657	**4.37**	3225	293	**NO GOOD**
		16	0.615	**4.35**	3526	313	**NO GOOD**
8 ft - Third Points, 2 braces each	663	12	0.766	**4.43**	2418	253	**NO GOOD**
		16	0.706	**4.40**	2732	273	**NO GOOD**
6 ft - Third Points, no bracing	0	12	0.480	**4.29**	4938	412	**NO GOOD**
		16	0.478	**4.29**	4942	412	**NO GOOD**
6 ft - Third Points, 1 brace each	669	12	0.768	**4.43**	2402	252	**NO GOOD**
		16	0.708	**4.41**	2716	273	**NO GOOD**
6 ft - Third Points, 2 braces each	1272	12	0.930	**4.54**	1320	198	**NO GOOD**
		16	0.845	**4.50**	1622	218	**NO GOOD**

Table 2.15 *Horizontal boards, pinned posts, L = 24 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	3.221	**1.06**	390	51	**OKAY**
		18	2.791	**1.02**	506	49	**OKAY**
		24	2.037	**1.02**	494	49	**OKAY**
10 ft - Outer corners, no bracing	291	12	3.283	**1.06**	378	49	**OKAY**
		18	2.792	**1.02**	503	49	**OKAY**
		24	2.037	**1.02**	492	49	**OKAY**
10 ft - Outer corners, 1 brace each	452	12	3.309	**1.06**	369	49	**OKAY**
		18	2.792	**1.02**	500	49	**OKAY**
		24	2.038	**1.02**	491	49	**OKAY**
10 ft - Outer corners, 2 braces each	588	12	3.332	**1.06**	363	48	**OKAY**
		18	2.792	**1.02**	498	49	**OKAY**
		24	2.038	**1.02**	489	49	**OKAY**
8 ft - Outer corners, no bracing	569	12	3.329	**1.06**	363	48	**OKAY**
		18	2.792	**1.02**	498	49	**OKAY**
		24	2.038	**1.02**	489	49	**OKAY**
8 ft - Outer corners, 1 brace each	816	12	3.369	**1.05**	351	48	**OKAY**
		18	2.793	**1.02**	495	49	**OKAY**
		24	2.038	**1.02**	487	49	**OKAY**
8 ft - Outer corners, 2 braces each	1036	12	3.406	**1.05**	340	47	**OKAY**
		18	2.794	**1.02**	491	48	**OKAY**
		24	2.038	**1.02**	485	49	**OKAY**
6 ft - Outer corners, no bracing	1348	12	3.457	**1.05**	328	46	**OKAY**
		18	2.794	**1.02**	486	48	**OKAY**
		24	2.038	**1.02**	482	48	**OKAY**
6 ft - Outer corners, 1 brace each	1753	12	3.524	**1.05**	311	45	**OKAY**
		18	2.796	**1.02**	480	48	**OKAY**
		24	2.039	**1.02**	478	48	**OKAY**
6 ft - Outer corners, 2 braces each	2130	12	3.587	**1.05**	299	44	**OKAY**
		18	2.797	**1.02**	475	48	**OKAY**
		24	2.039	**1.02**	475	48	**OKAY**

Table 2.16 *Diagonal Boards, Embedded Posts, L = 12 ft. from Building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.913	**3.05**	3179	285	**OKAY**
10 ft - Outer corners, Midspan , no bracing	583	12	1.087	**1.39**	2731.576	259.3	**OKAY**
10 ft - Outer corners, Midspan , 1 brace each	904	12	1.152	**1.37**	2356	238	**OKAY**
10 ft - Outer corners, Midspan , 2 braces each	1176	12	1.208	**1.36**	1979	207	**OKAY**
8 ft - Outer corners, Midspan , no bracing	1138	12	1.200	**1.36**	2036	212	**OKAY**
8 ft - Outer corners, Midspan , 1 brace each	1632	12	1.301	**1.34**	1292	142	**OKAY**
8 ft - Outer corners, Midspan , 2 braces each	2073	12	1.391	**1.31**	960	112	**OKAY**
6 ft - Outer corners, Midspan , no bracing	2697	12	1.518	**1.28**	780	94	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	3506	12	1.683	**1.24**	549	73	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	4260	12	1.836	**1.20**	504	70	**OKAY**

Table 2.17 *Diagonal boards, embedded posts, L = 18 ft. from building.* Substructure stiffnesses, Compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.692	**3.52**	5115	318	**OKAY**
10 ft - Outer corners, Midspan , no bracing	583	12	0.954	**3.25**	4356	290	**OKAY**
10 ft - Outer corners, Midspan , 1 brace each	904	12	1.076	**3.04**	3719	268	**OKAY**
10 ft - Outer corners, Midspan , 2 braces each	1176	12	1.159	**2.27**	3214	241	**OKAY**
8 ft - Outer corners, Midspan , no bracing	1138	12	1.148	**2.35**	3282	246	**OKAY**
8 ft - Outer corners, Midspan , 1 brace each	1632	12	1.277	**1.75**	2399	192	**OKAY**
8 ft - Outer corners, Midspan , 2 braces each	2073	12	1.378	**1.52**	2016	161	**OKAY**
6 ft - Outer corners, Midspan , no bracing	2697	12	1.497	**1.39**	1829	132	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	3506	12	1.632	**1.28**	1587	95	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	4260	12	1.733	**1.24**	1367	87	**OKAY**

Table 2.18 *Diagonal boards, embedded posts, L = 21 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.563	**3.59**	6739	349	**OKAY**
10 ft - Outer corners, Midspan , no bracing	1748	12	1.101	**2.27**	3828	253	**OKAY**
10 ft - Outer corners, Midspan , 1 brace each	2713	12	1.270	**1.55**	2603	182	**OKAY**
10 ft - Outer corners, Midspan , 2 braces each	3529	12	1.387	**1.36**	1581	121	**OKAY**
8 ft - Outer corners, Midspan , no bracing	3413	12	1.372	**1.38**	1606	122	**OKAY**
8 ft - Outer corners, Midspan , 1 brace each	4896	12	1.539	**1.25**	1289	104	**OKAY**
8 ft - Outer corners, Midspan , 2 braces each	6218	12	1.656	**1.20**	1007	88	**OKAY**
6 ft - Outer corners, Midspan , no bracing	9081	12	1.695	**1.17**	838	75	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	10519	12	1.704	**1.16**	778	69	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	12779	12	1.718	**1.14**	683	61	**OKAY**

Table 2.19 *Diagonal boards, embedded posts, L = 24 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	3.221	**1.06**	390	51	**OKAY**
		18	2.791	**1.02**	506	49	**OKAY**
		24	2.037	**1.02**	494	49	**OKAY**
10 ft - Outer corners, no bracing	0	12	3.221	**1.06**	390	51	**OKAY**
		18	2.791	**1.02**	506	49	**OKAY**
		24	2.037	**1.02**	494	49	**OKAY**
10 ft - Outer corners, 1 brace each	74	12	3.238	**1.06**	387	51	**OKAY**
		18	2.791	**1.02**	505	49	**OKAY**
		24	2.037	**1.02**	494	49	**OKAY**
10 ft - Outer corners, 2 braces each	131	12	3.252	**1.06**	385	50	**OKAY**
		18	2.791	**1.02**	505	49	**OKAY**
		24	2.037	**1.02**	493	49	**OKAY**
8 ft - Outer corners, no bracing	0	12	3.221	**1.06**	390	51	**OKAY**
		18	2.791	**1.02**	506	49	**OKAY**
		24	2.037	**1.02**	494	49	**OKAY**
8 ft - Outer corners, 1 brace each	121	12	3.249	**1.06**	385	50	**OKAY**
		18	2.791	**1.02**	505	49	**OKAY**
		24	2.037	**1.02**	493	49	**OKAY**
8 ft - Outer corners, 2 braces each	221	12	3.271	**1.06**	381	50	**OKAY**
		18	2.791	**1.02**	504	49	**OKAY**
		24	2.037	**1.02**	493	49	**OKAY**
6 ft - Outer corners, no bracing	0	12	3.221	**1.06**	390	51	**OKAY**
		18	2.791	**1.02**	506	49	**OKAY**
		24	2.037	**1.02**	494	49	**OKAY**
6 ft - Outer corners, 1 brace each	223	12	3.271	**1.06**	381	50	**OKAY**
		18	2.791	**1.02**	504	49	**OKAY**
		24	2.037	**1.02**	493	49	**OKAY**
6 ft - Outer corners, 2 braces each	424	12	3.305	**1.06**	371	49	**OKAY**
		18	2.792	**1.02**	501	49	**OKAY**
		24	2.037	**1.02**	491	49	**OKAY**

Table 2.20 *Diagonal boards, pinned posts, L = 12 ft. from building.* Substructure stiffnesses, Compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.913	**3.05**	3179	285	**OKAY**
10 ft - Outer corners, Midspan , no bracing	0	12	0.913	**3.05**	3179	285	**OKAY**
10 ft - Outer corners, Midspan , 1 brace each	148	12	0.984	**1.84**	3138	283	**OKAY**
10 ft - Outer corners, Midspan , 2 braces each	262	12	1.022	**1.41**	3106	281	**OKAY**
8 ft - Outer corners, Midspan , no bracing	0	12	0.913	**3.05**	3179	285	**OKAY**
8 ft - Outer corners, Midspan , 1 brace each	242	12	1.018	**1.41**	3130	282	**OKAY**
8 ft - Outer corners, Midspan , 2 braces each	442	12	1.058	**1.40**	2896	269	**OKAY**
6 ft - Outer corners, Midspan , no bracing	0	12	0.913	**3.05**	3179	285	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	446	12	1.059	**1.40**	2892	268	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	848	12	1.141	**1.38**	2422	242	**OKAY**

Table 2.21 *Diagonal boards, pinned posts, L = 18 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.692	**3.52**	5115	318	**OKAY**
10 ft - Outer corners, Midspan , no bracing	0	12	0.692	**3.52**	5115	318	**OKAY**
10 ft - Outer corners, Midspan , 1 brace each	148	12	0.771	**3.41**	5046	315	**OKAY**
10 ft - Outer corners, Midspan , 2 braces each	262	12	0.824	**3.35**	4992	313	**OKAY**
8 ft - Outer corners, Midspan , no bracing	0	12	0.692	**3.52**	5115	318	**OKAY**
8 ft - Outer corners, Midspan , 1 brace each	242	12	0.816	**3.36**	5032	315	**OKAY**
8 ft - Outer corners, Midspan , 2 braces each	442	12	0.897	**3.30**	4635	300	**OKAY**
6 ft - Outer corners, Midspan , no bracing	0	12	0.692	**3.52**	5115	318	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	446	12	0.899	**3.29**	4627	300	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	848	12	1.057	**3.12**	3830	271	**OKAY**

Table 2.22 *Diagonal boards, pinned posts, L = 21 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Substructure Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	12	0.563	**3.59**	6739	349	**OKAY**
10 ft - Outer corners, Midspan , no bracing	0	12	0.563	**3.59**	6739	349	**OKAY**
10 ft - Outer corners, Midspan , 1 brace each	222	12	0.667	**3.47**	6678	347	**OKAY**
10 ft - Outer corners, Midspan , 2 braces each	393	12	0.729	**3.43**	6202	331	**OKAY**
8 ft - Outer corners, Midspan , no bracing	0	12	0.563	**3.59**	6739	349	**OKAY**
8 ft - Outer corners, Midspan , 1 brace each	363	12	0.718	**3.44**	6286	334	**OKAY**
8 ft - Outer corners, Midspan , 2 braces each	663	12	0.827	**3.37**	5451	305	**OKAY**
6 ft - Outer corners, Midspan , no bracing	0	12	0.563	**3.59**	6739	349	**OKAY**
6 ft - Outer corners, Midspan , 1 brace each	669	12	0.829	**3.37**	5434	304	**OKAY**
6 ft - Outer corners, Midspan , 2 braces each	1272	12	0.998	**3.35**	4264	265	**OKAY**

Table 2.23 *Diagonal boards, pinned posts, L = 24 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Stiffness, K (lb/in)	Substructure Stiffness, K (N/mm)	(1:1, 12'x12') Dynamic Amplification Factor, Ck	(1:1, 16'x16') Dynamic Amplification Factor, Ck
0	0	**4.15**	**4.24**
200	35	**3.44**	**4.35**
300	53	**2.7**	**4.4**
400	70	**2.3**	**4.45**
600	105	**1.91**	**4.58**
800	140	**1.72**	**4.37**
1000	175	**1.61**	**3.52**
1200	210	**1.54**	**3**
1800	315	**1.42**	**2.32**
2200	385	**1.37**	**2.13**
3200	560	**1.31**	**1.89**
4200	736	**1.28**	**1.78**
5200	911	**1.26**	**1.72**
6500	1138	**1.24**	**1.67**
4.00E+09	7.00E+08	**1.18**	**1.49**

Table 2.24 Comparison of amplification factors between 12'x12' and 16'x16' deck

Substructure Stiffness, K (lb/in)	Substructure Stiffness, K (N/mm)	(1.5:1, 18'x12') Dynamic Amplification Factor, Ck	(1.5:1, 24'x16') Dynamic Amplification Factor, Ck
0	0	**4.25**	**4.29**
200	35	**4.3**	**4.32**
500	88	**4.38**	**4.38**
750	131	**4.44**	**4.42**
1000	175	**4.3**	**4.46**
1500	263	**2.65**	**4.5**
2500	438	**1.88**	**4.53**
3500	613	**1.65**	**3.58**
4500	788	**1.54**	**2.78**
5500	963	**1.48**	**2.41**
6500	1138	**1.43**	**2.2**
4.00E+09	7.00E+08	**1.23**	**1.47**

Table 2.25 Comparison of amplification factors between 18'x12' and 24'x16' deck

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.712	1056	4476	4698	19911	**4.24**
200	35	0.839	1056	4597	4698	20450	**4.35**
300	53	0.890	1056	4651	4698	20688	**4.40**
400	70	0.937	1056	4700	4698	20906	**4.45**
500	88	0.978	1056	4766	4698	21200	**4.51**
600	105	1.015	1056	4833	4698	21497	**4.58**
700	123	1.049	1056	4846	4698	21555	**4.59**
800	140	1.079	1056	4617	4698	20537	**4.37**
900	158	1.107	1056	4126	4698	18353	**3.91**
1000	175	1.133	1056	3717	4698	16536	**3.52**
1200	210	1.178	1056	3166	4698	14083	**3.00**
1400	245	1.216	1056	2830	4698	12589	**2.68**
1600	280	1.249	1056	2609	4698	11603	**2.47**
1800	315	1.277	1056	2452	4698	10908	**2.32**
2200	385	1.324	1056	2248	4698	9998	**2.13**
3200	560	1.401	1056	1999	4698	8891	**1.89**
4200	736	1.448	1056	1884	4698	8380	**1.78**
5200	911	1.478	1056	1818	4698	8086	**1.72**
6500	1138	1.505	1056	1765	4698	7851	**1.67**
4.0E+09	7.0E+08	1.621	1056	1574	4698	6999	**1.49**

Table 2.26 Model Results: 16x16, 1:1 aspect ratio, horizontal deck boards

Substructure Stiffness, K		Natural Frequency (Hz)	Total Resultant Shear Force (lb)		Total Resultant Shear Force (N)		Dynamic Amplification Factor, Ck
(lb/in)	(N/mm)		Static	Dynamic	Static	Dynamic	
0	0	0.478	1600	6861	7117	30521	**4.29**
200	35	0.561	1600	6919	7117	30775	**4.32**
500	88	0.661	1600	7002	7117	31148	**4.38**
750	131	0.730	1600	7069	7117	31446	**4.42**
1000	175	0.789	1600	7133	7117	31729	**4.46**
1250	219	0.841	1600	7192	7117	31993	**4.50**
1500	263	0.888	1600	7247	7117	32237	**4.53**
2000	350	0.966	1600	7342	7117	32661	**4.59**
2250	394	1.000	1600	7379	7117	32823	**4.61**
2500	438	1.031	1600	7378	7117	32819	**4.61**
3000	525	1.085	1600	6944	7117	30888	**4.34**
3500	613	1.131	1600	5731	7117	25491	**3.58**
4000	701	1.170	1600	4951	7117	22024	**3.09**
4500	788	1.204	1600	4450	7117	19795	**2.78**
5500	963	1.260	1600	3859	7117	17166	**2.41**
6500	1138	1.303	1600	3526	7117	15683	**2.20**
4.0E+09	7.0E+08	1.628	1600	2347	7117	10440	**1.47**

Table 2.27 Model Results: 24x16, 1.5:1 aspect ratio, horizontal deck boards

Substructure Description	Total Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	16	0.712	**4.24**	2170	271	**NO GOOD**
10 ft - Outer corners, no bracing	291	16	0.886	**4.40**	1622	224	**NO GOOD**
10 ft - Outer corners, 1 brace each	452	16	0.958	**4.48**	1395	207	**NO GOOD**
10 ft - Outer corners, 2 braces each	588	16	1.011	**4.57**	1202	192	**NO GOOD**
8 ft - Outer corners, no bracing	569	16	1.004	**4.56**	1229	194	**NO GOOD**
8 ft - Outer corners, 1 brace each	816	16	1.084	**4.30**	880	167	**NO GOOD**
8 ft - Outer corners, 2 braces each	1036	16	1.141	**3.43**	604	144	**NO GOOD**
6 ft - Outer corners, no bracing	1348	16	1.206	**2.76**	464	121	**NO GOOD**
6 ft - Outer corners, 1 brace each	1753	16	1.271	**2.36**	283	92	**NO GOOD**
6 ft - Outer corners, 2 braces each	2130	16	1.316	**2.16**	234	84	**NO GOOD**

Table 2.28 *Horizontal boards, embedded posts, L = 16 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

Substructure Description	Total Stiffness (lb/in)	Width Along Building (ft)	Natural Frequency (Hz)	Dynamic Amplification Factor, Ck	Total Force Resisting Overturning (lb)	Unit Shear (lb/ft)	Unit Shear Check (lb/ft)
No Substructure	0	16	0.712	**4.24**	2170	271	**NO GOOD**
10 ft - Outer corners, no bracing	0	16	0.712	**4.24**	2170	271	**NO GOOD**
10 ft - Outer corners, 1 brace each	74	16	0.759	**4.28**	2015	257	**NO GOOD**
10 ft - Outer corners, 2 braces each	131	16	0.795	**4.31**	1895	247	**NO GOOD**
8 ft - Outer corners, no bracing	0	16	0.712	**4.24**	2170	271	**NO GOOD**
8 ft - Outer corners, 1 brace each	121	16	0.788	**4.31**	1916	249	**NO GOOD**
8 ft - Outer corners, 2 braces each	221	16	0.849	**4.36**	1721	232	**NO GOOD**
6 ft - Outer corners, no bracing	0	16	0.712	**4.24**	2170	271	**NO GOOD**
6 ft - Outer corners, 1 brace each	223	16	0.850	**4.36**	1718	232	**NO GOOD**
6 ft - Outer corners, 2 braces each	424	16	0.946	**4.46**	1434	210	**NO GOOD**

Table 2.29 *Horizontal boards, pinned posts, L = 16 ft. from building.* Substructure stiffnesses, compilation of amplification factors, overturning forces, and unit shear checks.

2.8 Figures

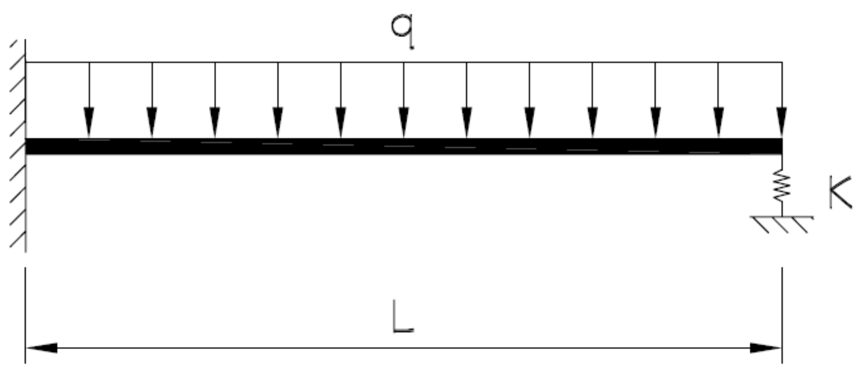


Figure 2.1: Shear beam structural analog for deck with supports at end

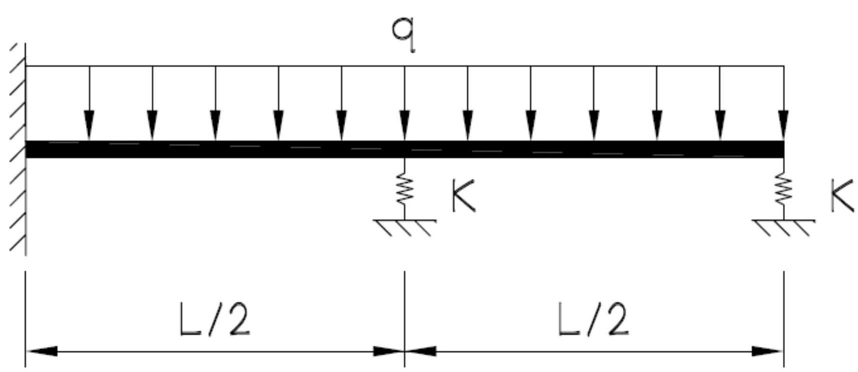


Figure 2.2: Shear beam structural analog for deck with supports at end and midpsan

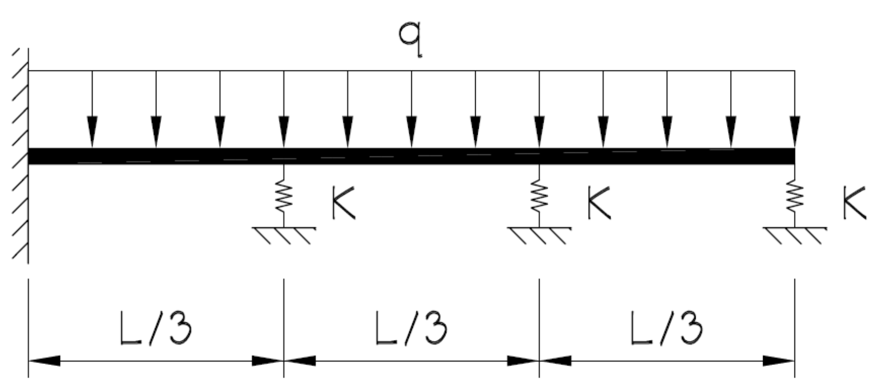


Figure 2.3: Shear beam structural analog for deck with supports at third points

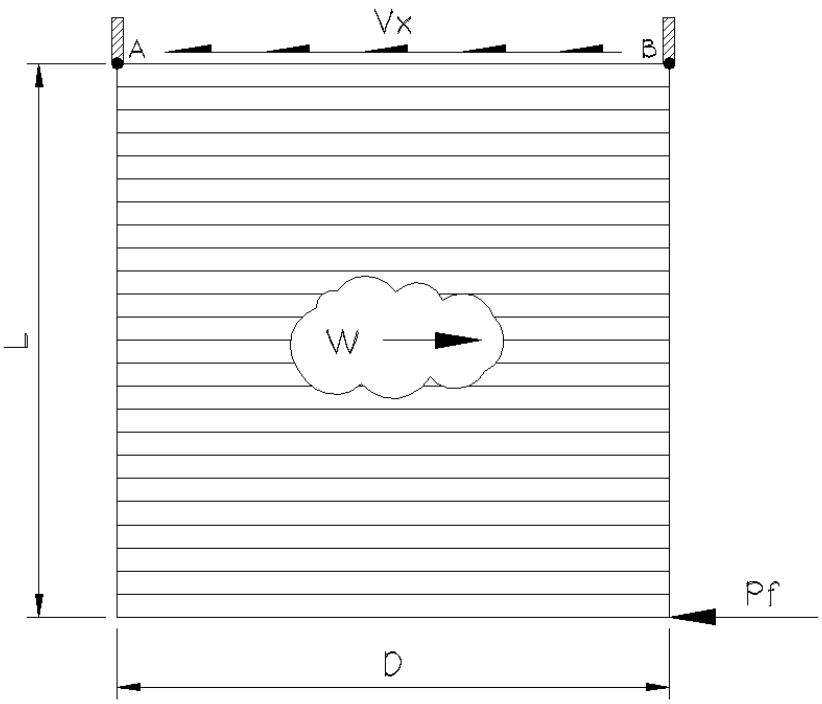


Figure 2.4: Decks with supports at end - hand-calc schematic (1:1, 1:1.5, 1:2 ratio)

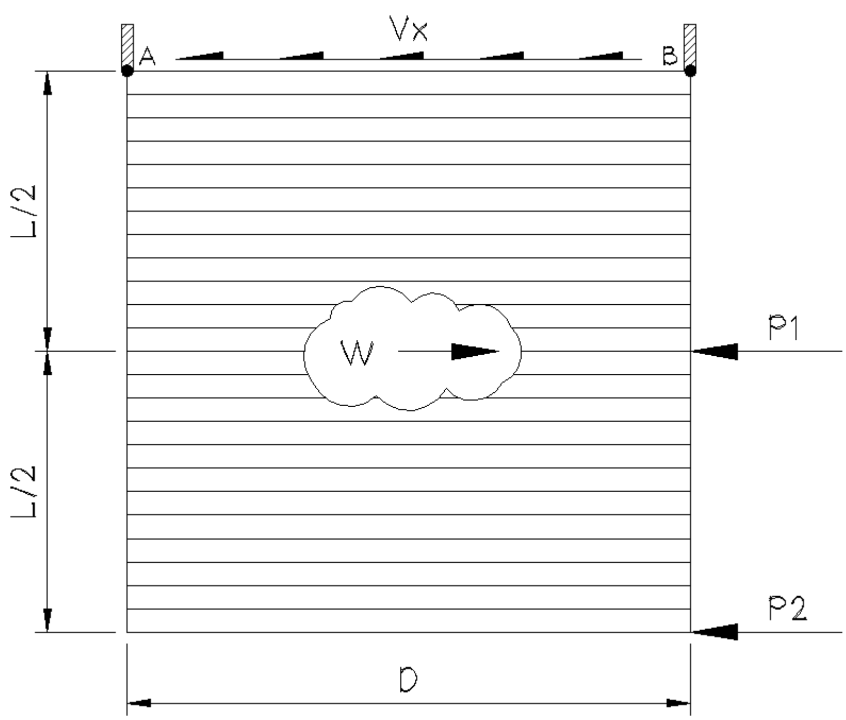


Figure 2.5: Decks with supports at end and midspan - hand-calc schematic (1.5:1, 1:75:1 ratio)

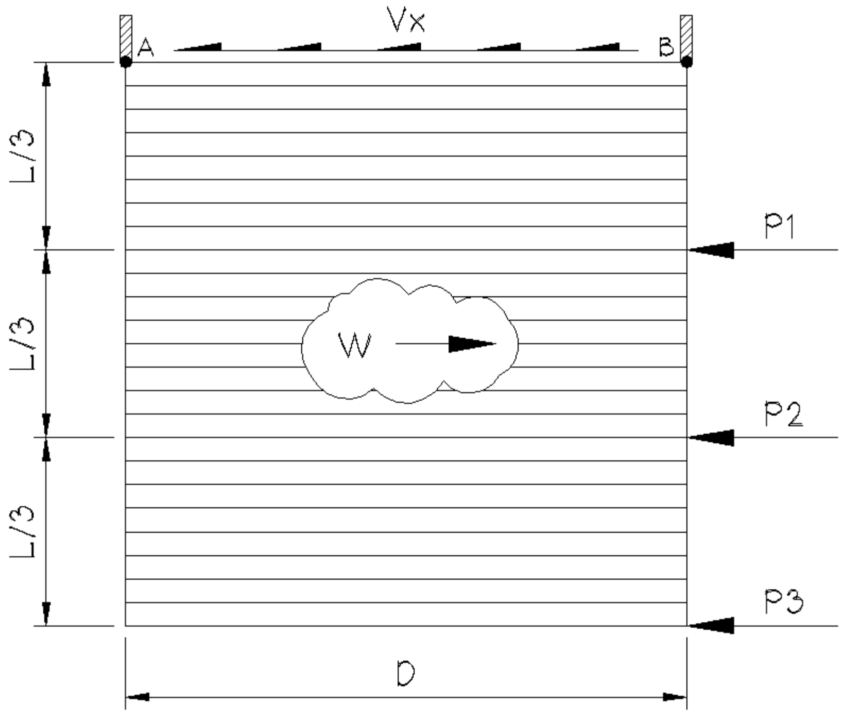


Figure 2.6: Decks with supports at third points - hand-calc schematic (2:1 ratio)

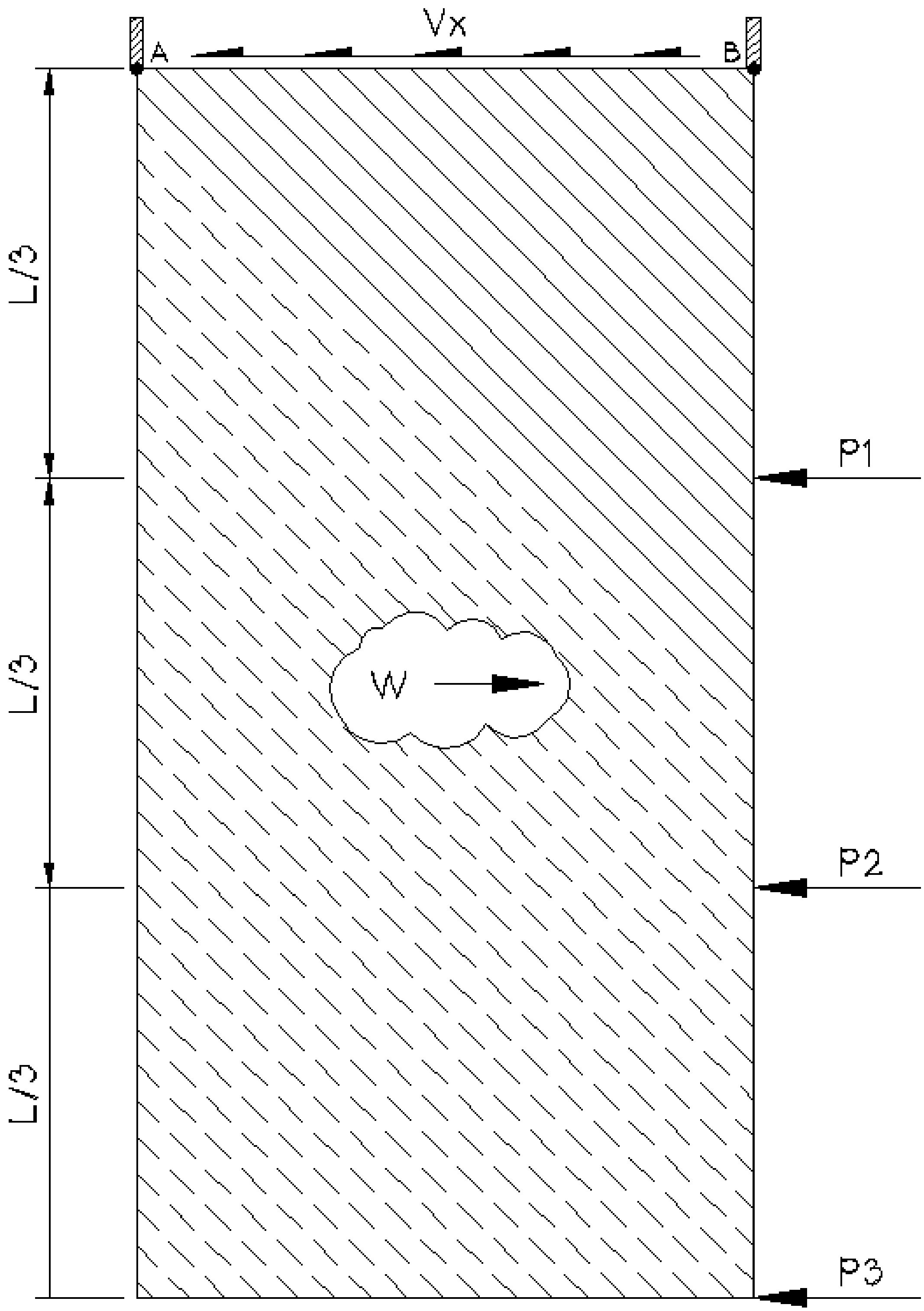


Figure 2.7: Only diagonal deck boards within 1:1 aspect ratio transfer loads directly into building ledger. All other diagonal deck boards span between the outermost joists (shown as dashed lines)

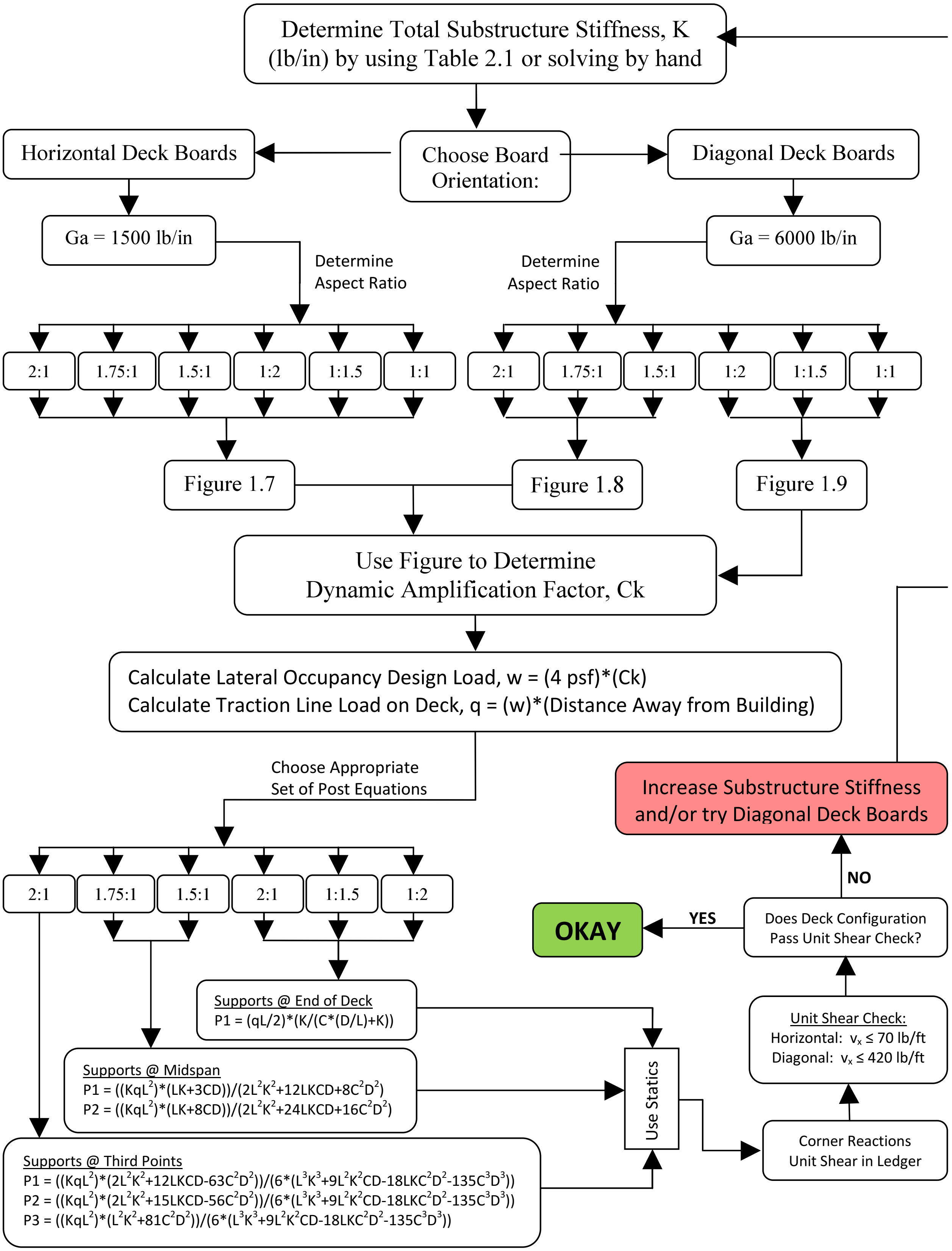


Figure 2.8: Design flowchart depicting process of designing for lateral loads due to occupancy

APPENDIX A: DYNAMIC AMPLIFCATION CURVE ANOMALIES EXPLAINED

Frequency Sweeps

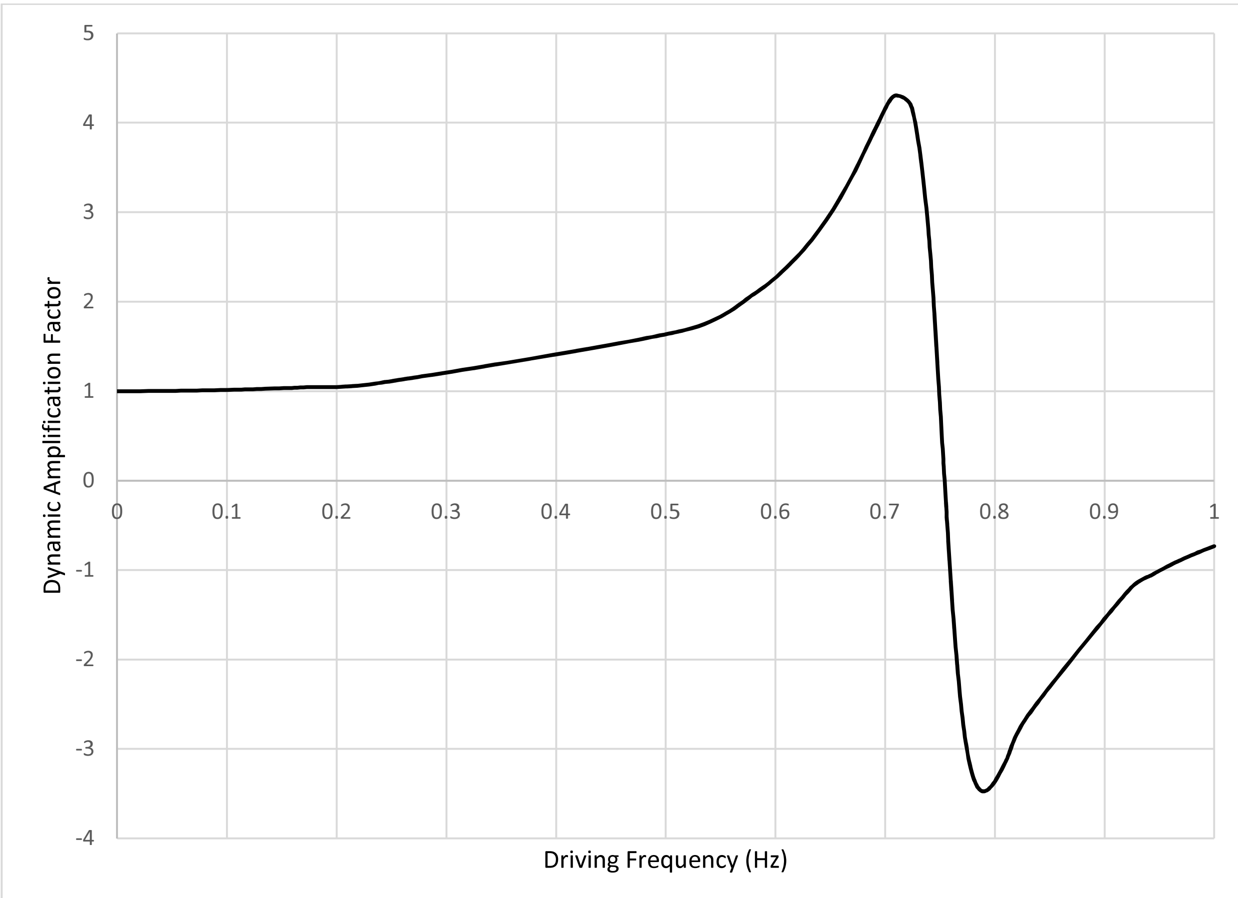


Figure A.1 Example frequency sweep - horizontal boards, 1.5:1 aspect ratio, Substructure stiffness = 200 lb/in. As the driving frequency approaches the natural frequency of the structure, dynamic amplification increases. A phase shift/sign change occurs directly at the natural frequency.

The dynamic amplification curves developed and presented in this study are based on an excitation frequency of 1 Hz. Previous research indicated that occupants generating a cyclic lateral load could achieve a maximum frequency of 1 Hz (Parsons et al. 2014b). When the natural frequency of a deck configuration is equal to 1 Hz, the maximum dynamic amplification is achieved. Then, were it not for damping, the amplification approaching the natural frequency would become infinite.

It is possible for a deck configuration to have a natural frequency less than 1 Hz, particularly for aspect ratios extending away from the primary structure. In these scenarios, as the dynamic driving load is ramping up to 1 Hz it reaches the structure's natural frequency. Therefore, for all applicable deck configurations, the values listed in the design tables and used to create the design curves correspond to the deck's maximum dynamic amplification at a frequency less than 1 Hz.

For example, examine the case of the 1.5:1 aspect ratio, horizontal deck boards, and 200 lb/in substructure stiffness (Table 1.4). The natural frequency of this deck configuration is 0.753 Hz. If occupants were to begin swaying back and forth to apply a dynamic lateral load to the deck, the load would begin at 0 Hz and work its way up to a maximum of 1 Hz. In this process, they would reach the natural frequency of 0.753 Hz. It is logical to assume that they would remain at this frequency, for the deck at this point is experiencing its greatest displacements and forces. The occupants would have the easiest time getting into synchronizations with the momentum of the deck's mass and keeping the deck moving, as observed in previous laboratory tests (Parsons et. al 2014b).

Figure A.1 shows the frequency sweep for this example. At the natural frequency, the phase angle flips, causing the observed sign change. The maximum dynamic amplification of 4.30 occurs at 0.708 Hz, right before reaching the natural frequency and the phase angle change. When the substructure stiffness is increased, so does the natural frequency of the deck. Table 1.4 shows that when the substructure stiffness is increased from 200 lb/in to 500 lb/in, natural frequency increases to 0.898 Hz. Shifting the natural frequency closer to 1 Hz increases the dynamic amplification factor to 4.38, as shown in Figure A.2. These increases will continue until natural frequency exceeds the driving function maximum of 1 Hz.

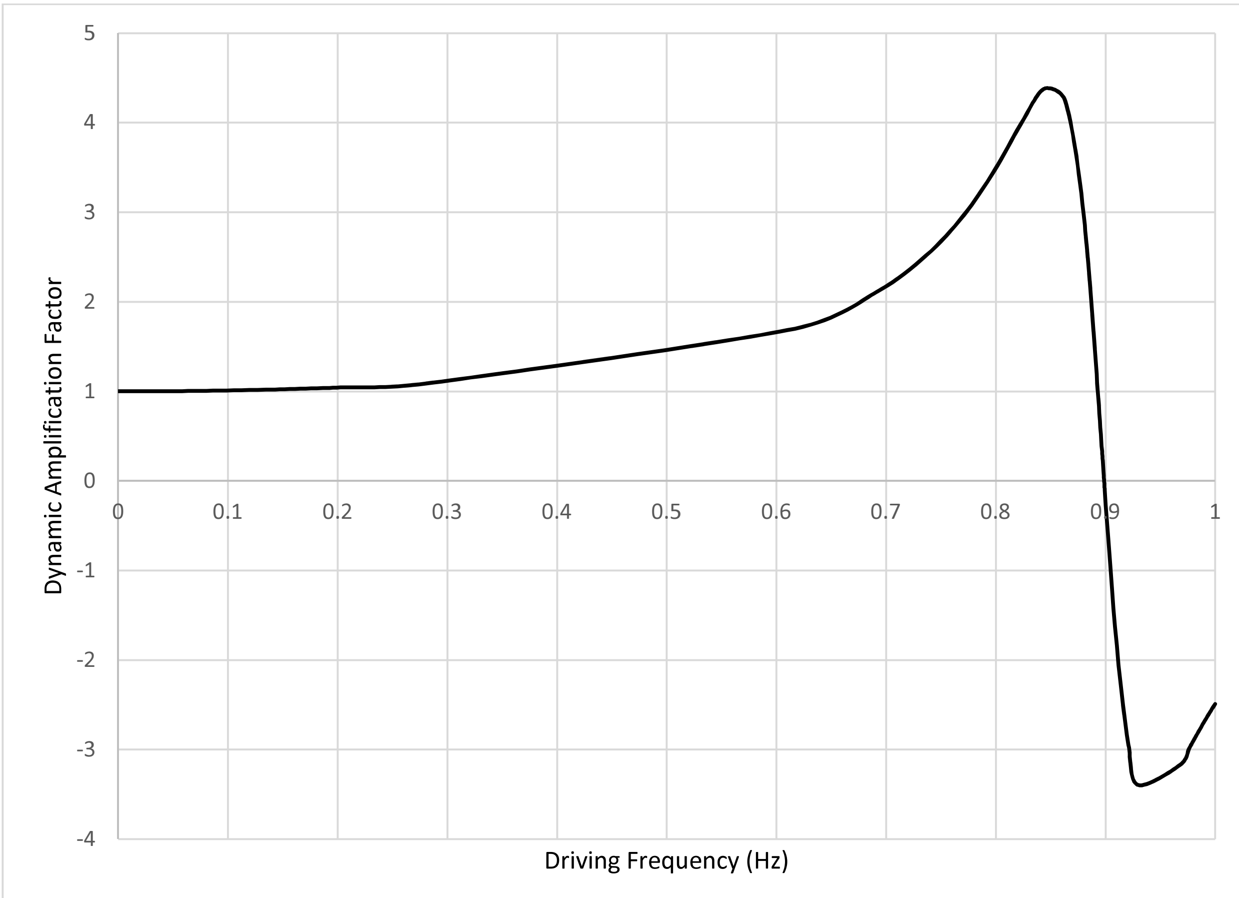


Figure A.2 Example frequency sweep - horizontal boards, 1.5:1 aspect ratio, Substructure stiffness = 500 lb/in. As the driving frequency approaches the natural frequency of the structure, dynamic amplification increases. A phase shift/sign change occurs directly at the natural frequency.

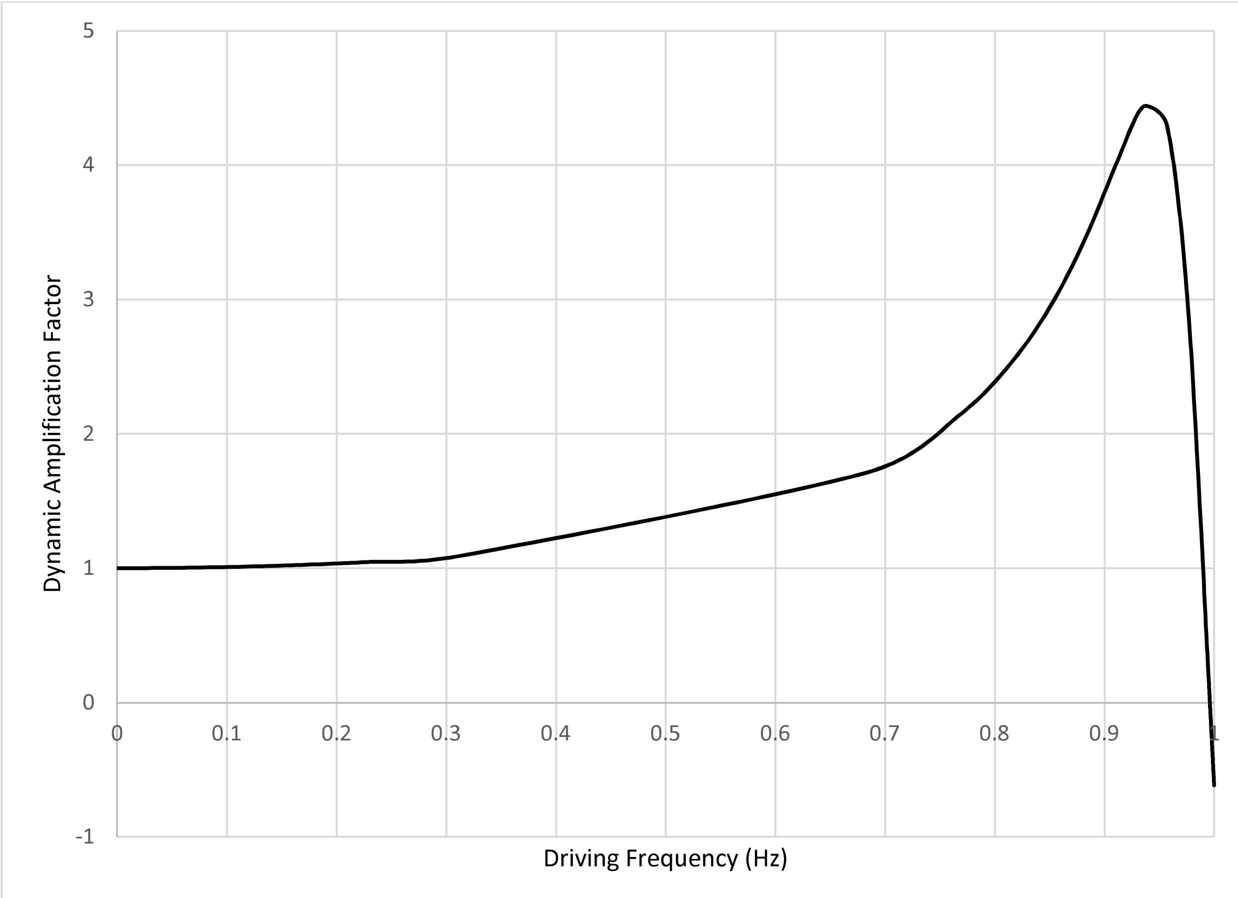


Figure A.3 Example frequency sweep - horizontal boards, 1.5:1 aspect ratio, substructure stiffness = 750 lb/in. As the driving frequency approaches the natural frequency of the structure, dynamic amplification increases. A phase shift/sign change occurs directly at the natural frequency. Note that the natural frequency is 0.995 Hz, essentially equal to 1 Hz.

When the substructure stiffness is further increased from 500 lb/in to 750 lb/in, the natural frequency is increased to 0.995 Hz. Effectively 1 Hz, the maximum dynamic amplification of 4.44 (Figure A.3) is the worst possible amplification this deck configuration could experience, since the driving function matches the natural frequency. From this point on, the maximum dynamic amplification factor will decrease as substructure stiffness continues to increase.

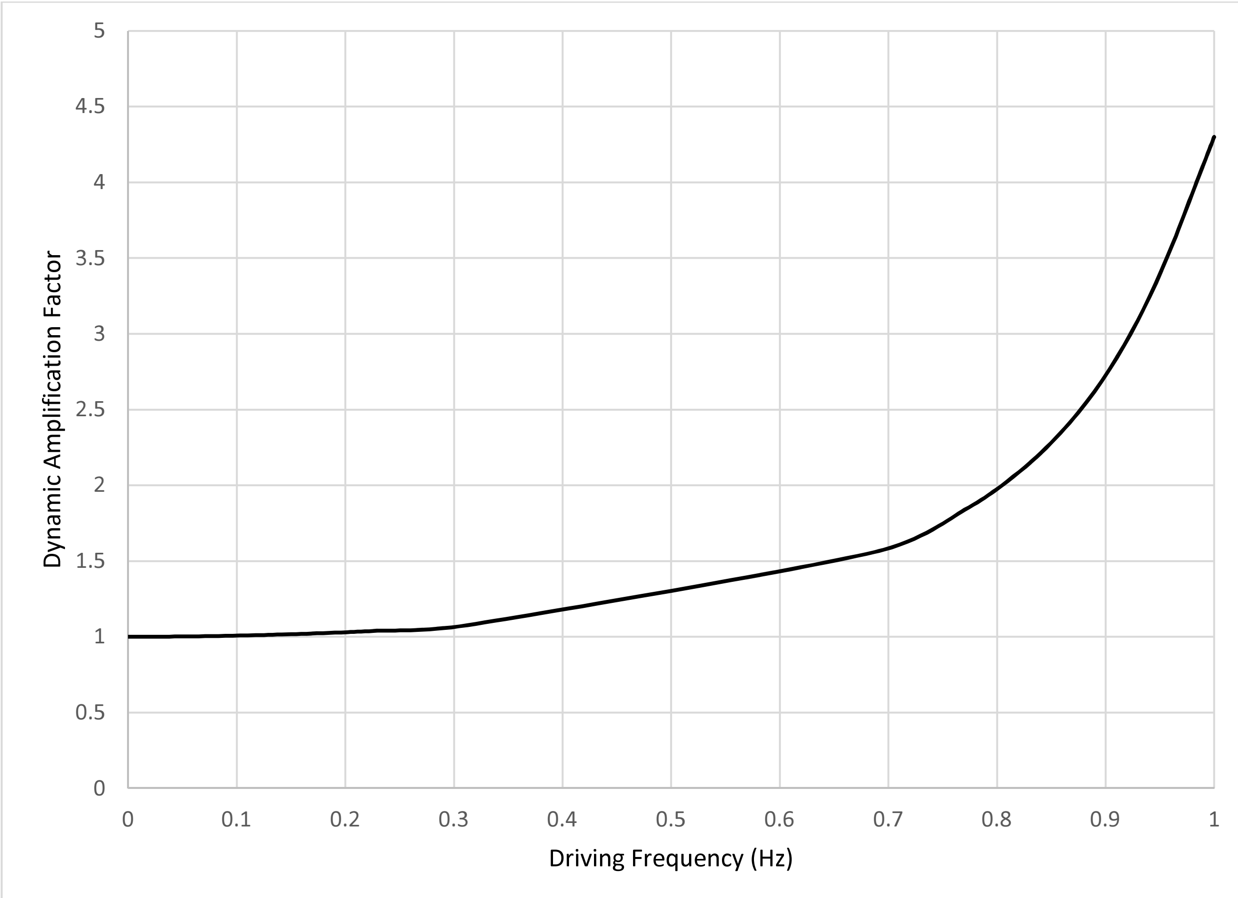


Figure A.4 Example frequency sweep - horizontal boards, 1.5:1 aspect ratio, substructure stiffness = 1000 lb/in. As the driving frequency approaches the natural frequency of the structure, dynamic amplification increases. A phase shift/sign change no longer occurs within shown frequency range because the natural frequency is greater than 1 Hz.

A stiffness increase from 750 lb/in to 1000 lb/in increases the natural frequency of the structure to 1.078 Hz. A natural frequency greater than the 1 Hz driving function causes the maximum dynamic amplification factor to decrease back down to 4.30. As seen in Figure A.4, the phase shift and sign change no longer occur within the range of the frequency sweep.

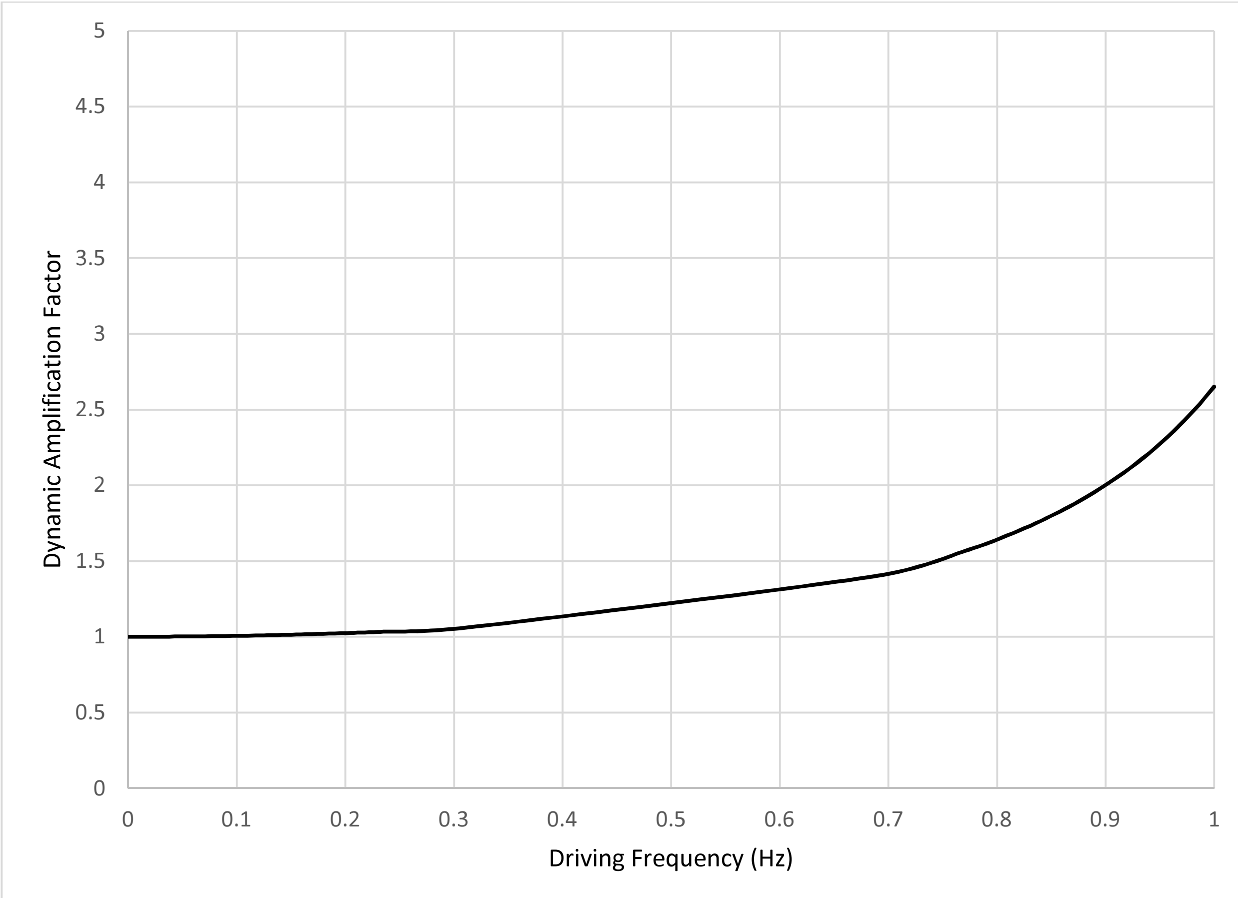


Figure A.5 Example frequency sweep - horizontal boards, 1.5:1 aspect ratio, substructure stiffness = 1500 lb/in. As the driving frequency approaches the natural frequency of the structure, dynamic amplification increases. A phase shift/sign change no longer occurs within shown frequency range because the natural frequency is greater than 1 Hz.

By increasing the substructure stiffness from 1000 lb/in to 1500 lb/in, a significant change in maximum amplification factor can be seen (Figure A.5). With the natural frequency increased to 1.212 Hz, the maximum dynamic amplification factor decreases to 2.65. This rapid drop in amplification factor can be seen in Figure 1.6. The further away from 1 Hz the natural frequency becomes, the smaller the maximum amplification factor. Eventually, if stiffness continues to increase, the frequency sweep plot would continue to flatten out until no observable

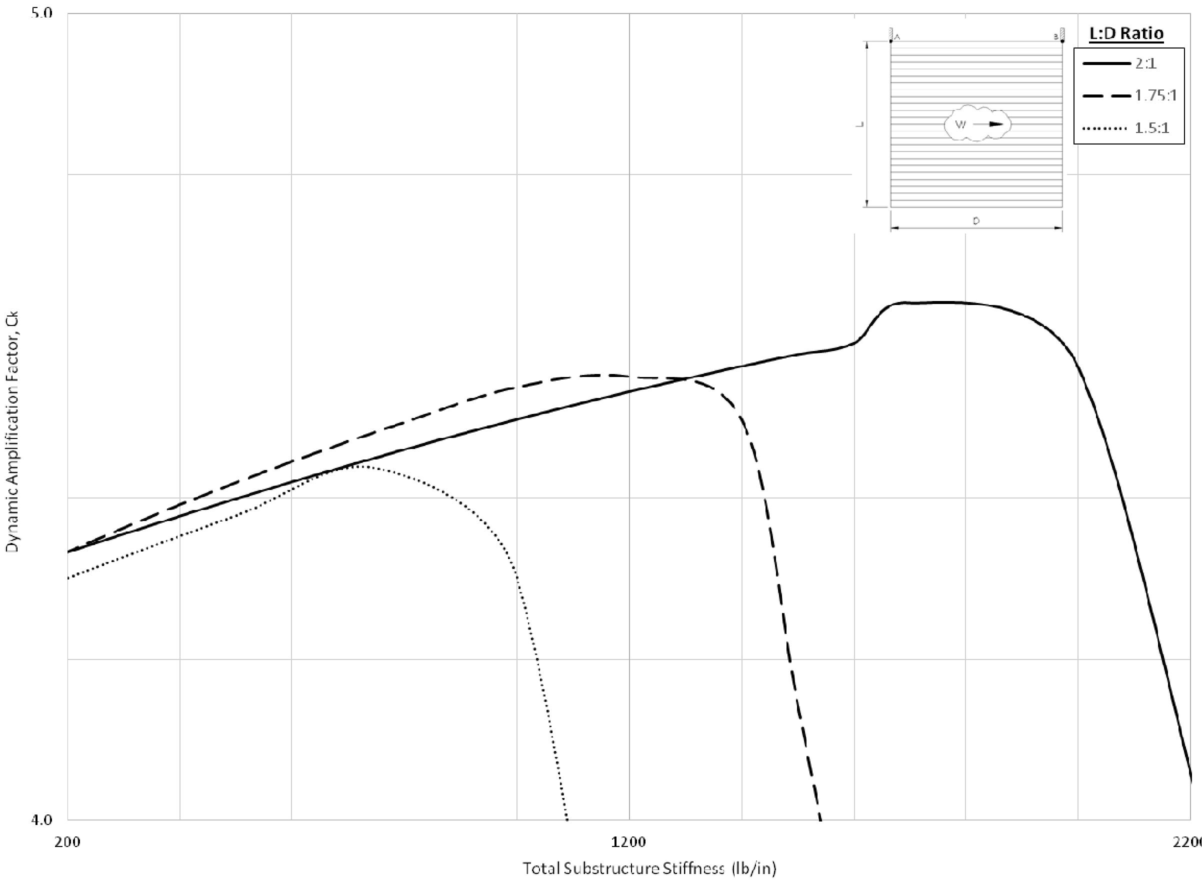


Figure A.6 Closer look at horizontal deckboard dynamic amplification curves for aspect ratios extending away from the primary structure. The sharp drop in amplification occurs when the frequency of the driving function surpasses the natural frequency of the particular deck configuration.

increase in amplification occurs. There would simply be horizontal line at 1.0 amplification factor.

Dynamic Amplification Curve Dropoff

One characteristic of the dynamic amplification curves that jumps out initially is the sharp drop in dynamic amplification factor that occurs on the left side of the charts. For the aspect ratios extending away from the primary structure (1.5:1, 1.75:1, 2:1), the amplification curves increase at low substructure stiffnesses and then each rapidly decrease at a certain point

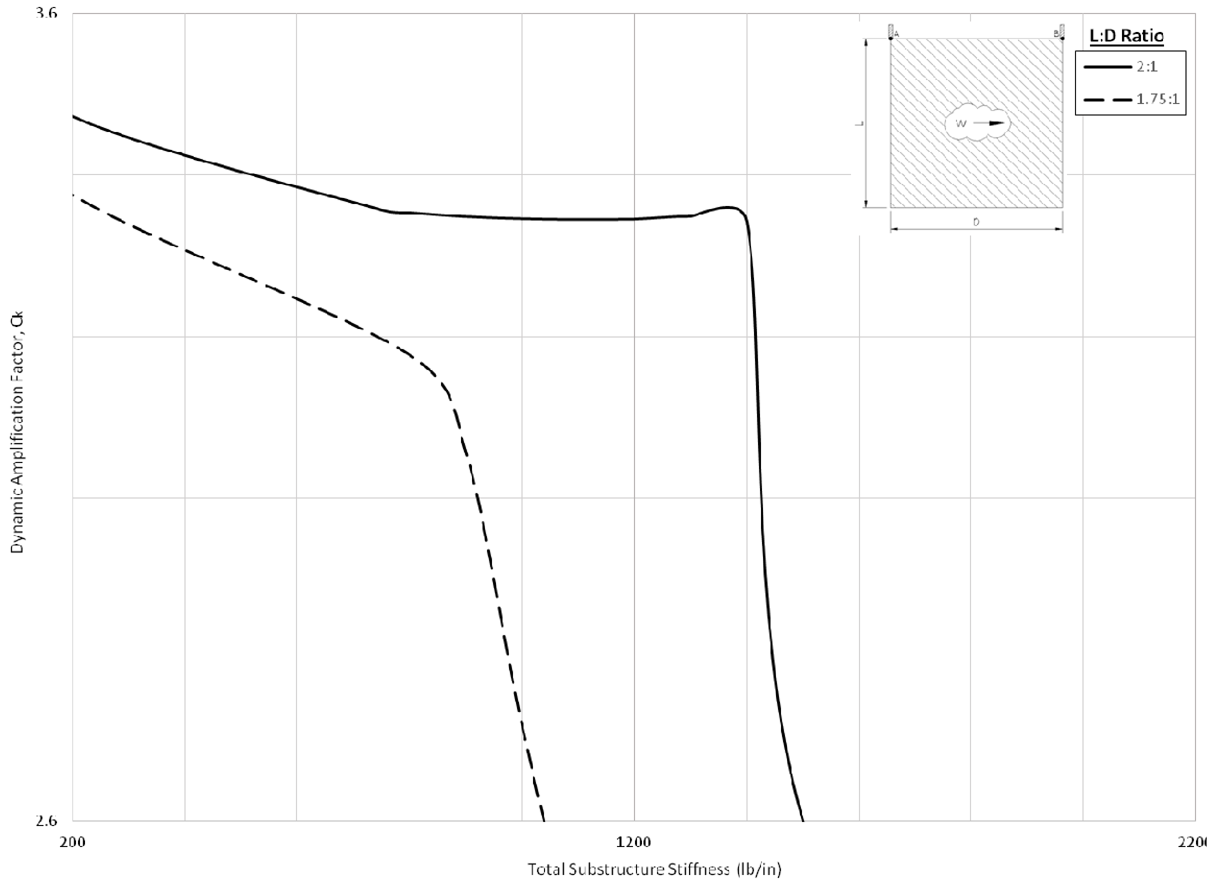


Figure A.7 Closer look at diagonal deckboard dynamic amplification curves for aspect ratios extending away from the primary structure. The sharp drop in amplification occurs when the frequency of the driving function surpasses the natural frequency of the particular deck configuration.

(Figures A.6, A.7). These sudden changes are the result of the structure's natural frequency increasing above 1 Hz.

As discussed with the frequency sweeps, increasing the substructure stiffness increases the natural frequency. The slight increase/plateau that occurs at lower stiffnesses corresponds to the natural frequency being less than 1 Hz. The dynamic amplification factor remains high because the driving function is able to match the natural frequency of the structure. When the

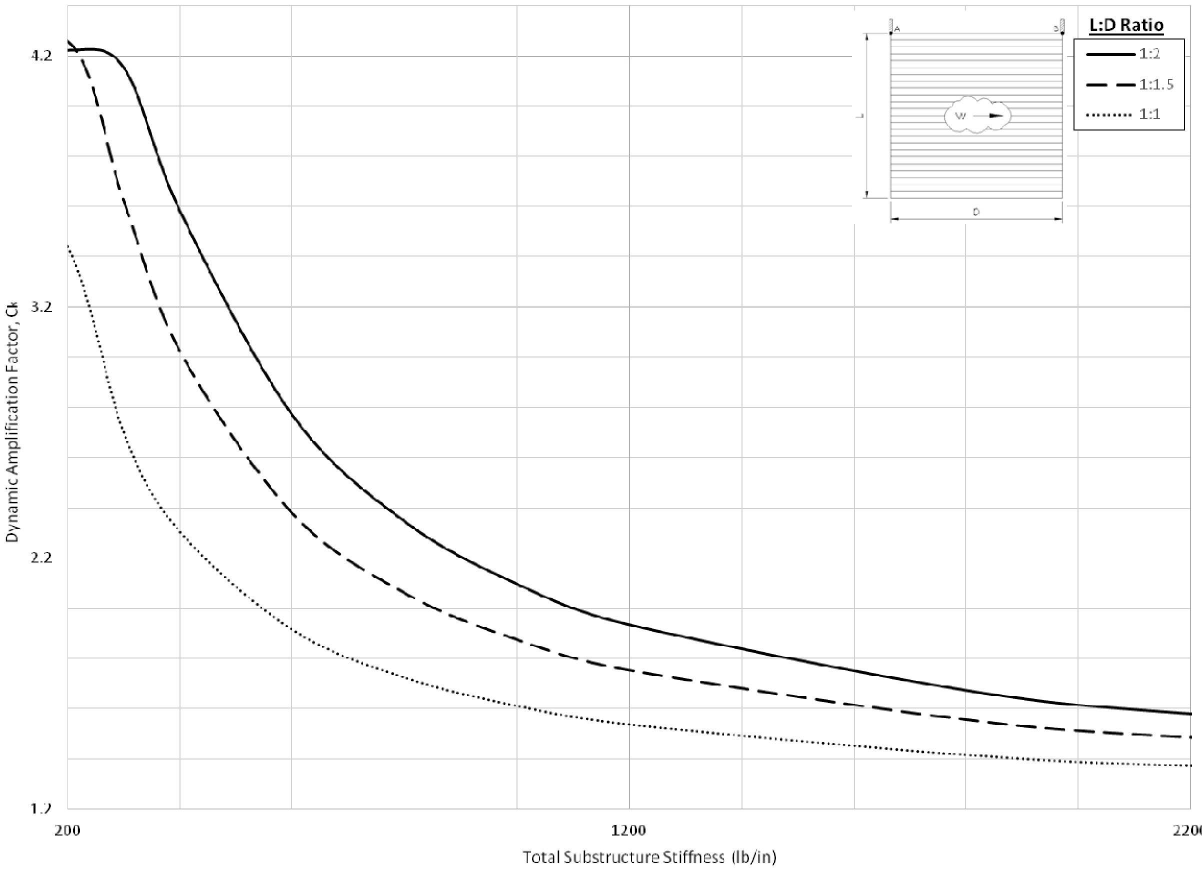


Figure A.8 Closer look at horizontal deckboard amplification curves for aspect ratios extending along the length of the primary structure. The curve order is a result of F=m*a, stiffness attracts load.

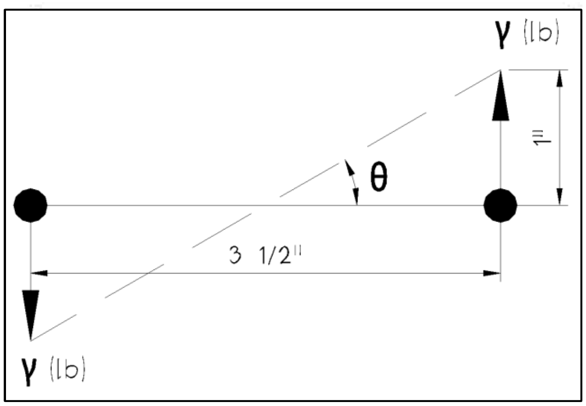
substructure stiffness is increased so that the natural frequency is above 1 Hz, the driving frequency does not reach the natural frequency, causing less amplification. The curves along the length of the primary structure (Figure A.8) do not have these sudden drops because they are stiffer and consequently at or above a natural frequency of 1 Hz.

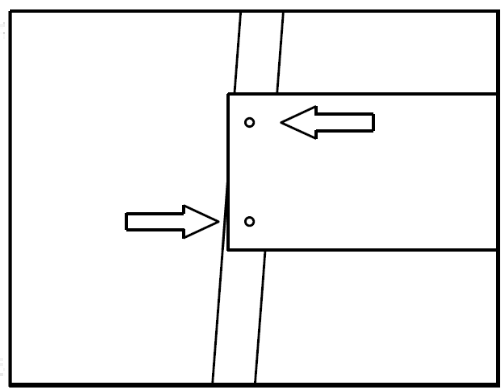
Order of curves

It is intuitive that the further you extend the deck along the primary structure without extending further out from the primary structure, the stiffer diaphragm you create. However, the order of the dynamic amplification curves is less clear. There are two things at work that cause 1:2 decks to have more amplification than 1:1 decks. The first is Newton's second law of motion: $F = m*a$. When the deck size increases, so does its mass. More mass creates more momentum when the deck sways back and forth, increasing amplification. The second is that stiffness attracts load. Even with the same substructure stiffness, a 1:2 deck has a stiffer diaphragm than a 1:1 deck and attracts more load. The corner post spacing also plays a factor in the force distributions.

APPENDIX B: SPRING STIFFNESS CALCULATIONS

Design Method:	Allowable Stress Design (ASD)
Connection Type:	Lateral Loading
Fastener Type:	Wood Screw
Loading Scenario:	Single Shear
Main Member Type:	Hem-Fir
Main Member Thickness:	9.25 in.
Main Member - Angle of Load to Grain:	90 degrees (Perpendicular)
Side Member Type:	Hem-Fir
Side Member Thickness:	1.5 in.
Side Member - Angle of Load to Grain:	0 degrees (Parallel)
Fastener Diameter:	(No. 8) 0.164 in.
Fastener Length:	3 in.





Slip Modulus:	γ =	11955	lb/in	[2012 NDS, § 10.3.6]
Deck Board Nail Spacing:	d =	3.5	in	
Angle, θ = ATAN((1in)/(d/2)) =		0.5714	radians	
Moment Arm, M :	γ * (d/2) =	20921	lb-in	
Rotational Stiffness:	k = M/θ	lb-in/radian		

k = 36611 lb-in/radian

Figure B.1: Example calculation sheet for deck board fastener rotational stiffness

APPENDIX C: EXAMPLE PROBLEM

(For wind and/or seismic load determination, see Lyman et. al. 2013)

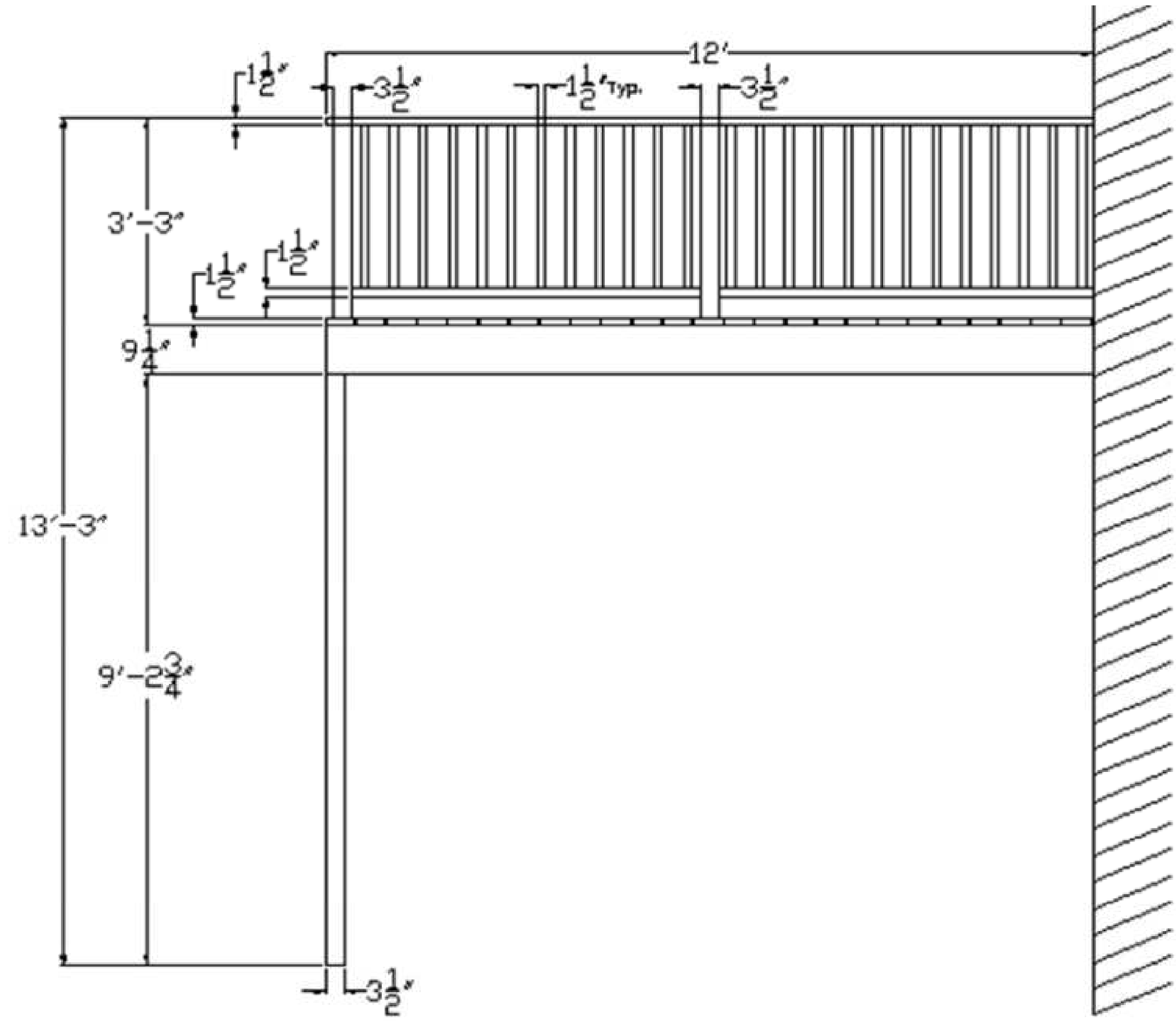


Figure C.1 Example deck configuration (Lyman et al. 2013a)

Given:

- 1:1 Aspect Ratio, 12 ft. by 12 ft.
- No. 2 Hem-Fir Lumber
- 2x12 Ledgers
- 2x10 Joists
- 2x4 Horizontal Deck Boards
- 4x4 deck posts, 9'-2 3/4" tall. Placed at outside corners, embedded, no knee braces.

Solution:

Substructure Stiffness

Cantilevered beam deflection = $PL^3/3EI$
For one inch of deflection, $P = 3EI/L^3$

L = 9.23 ft = 110.76 in
E = 1,100,000 psi [2012 NDS Supplement, Table 4D]
I = 12.51 in^4 [2012 NDS Supplement, Table 1B]

$$P = (3 * 1100000 * 12.51)/110.76^3 = 30.382\ lb$$

For two posts, $\boldsymbol{Substucture\ Stiffness,\ K = \ 61\ lb/in}$

Diaphragm Stiffness

For horizontal deck boards**,** $\boldsymbol{G_a = 1500\ lb/in}$ [AWC SDPWS 2008, Table 4.3D]

Dynamic Amplification Factor

Interpolating from Table 1.1 or Figure 1.6 for substructure stiffness of 61 lb/in, aspect ratio of 1:1 and horizontal deck board orientation yields a dynamic amplification factor of:

C_k = 3.93

Lateral Occupancy Design Load

$$w = \ (4\, psf) * 3.9 = \mathbf{15.7}\ \boldsymbol{psf}$$

Maximum Possible Force on Substructure

Assuming the diaphragm behaves like a simply supported beam:

$$q = w * L = \mathbf{189}\ \boldsymbol{lb/ft}$$

Reaction Force of Substructure

$$P_f = \frac{qL}{2} * \left[\frac{K}{\left(\frac{CD}{L} + K \right)} \right]$$

$$P_f = \frac{(189\ lb/ft) * (12\ ft)}{2} * \left[\frac{(61\ lb/in)}{\left(\frac{(1500\ lb/in) * (12\ ft)}{(12\ ft)} \right) + (61\ lb/in)} \right] = \boldsymbol{44\ lb}$$

Ledger Reactions at Primary Structure

Hold-down Forces:

$$A_y = \frac{(-(44\ lb) * (12\ ft)) + (15.7\ psf) * (12\ ft) * (12\ ft) * \left(\frac{12\ ft}{2} \right)}{12\ ft} = \boldsymbol{1,088\ lb}$$

$$B_y = A_y = \boldsymbol{1,088\ lb}$$

Unit Shear:

$$v_x = \frac{((15.7\ psf) * (12\ ft) * (12\ ft)) - 44\ lb}{12\ ft} = \boldsymbol{185\ lb/ft}$$

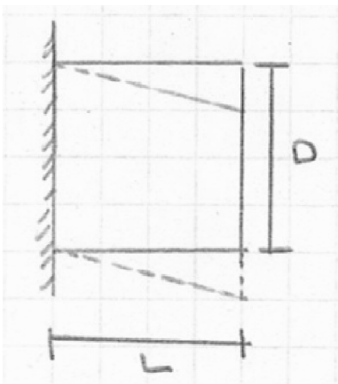
Allowable Check

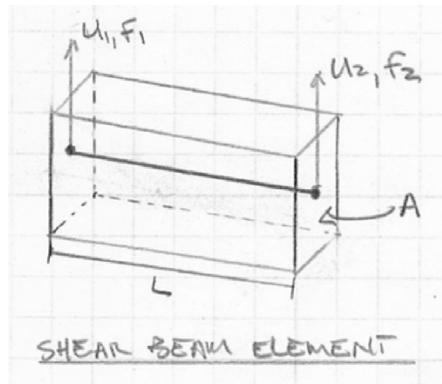
$$v_x = 185\ lb/ft \ > 70\ lb/ft$$ [AWC SDPWS 2008, Table 4.3D]

NO GOOD. Unit shear demand exceeds the allowable value for diaphragm. More stiffness needs to be added to the deck/substructure system to reduce dynamic amplification of lateral loads. One easy way to make this design check is to use diagonal deck boards. Appendix E shows printouts of the solution for horizontal and diagonal deck boards. With diagonal deck boards, the unit shear easily checks OK, and the hold-down forces are only 302 lb.

APPENDIX D: POST REACTION EQUATION DERIVATIONS

Consider the deck as a shear beam:





For a typical beam, the stiffness matrix is:

$$K = \frac{(5/6)AG}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$

$G = Shear\ modulus$
$A = Cross - sectional\ area$
$(5/6)\ is\ the\ correction\ factor\ for\ a\ rectangular\ cross\ section$

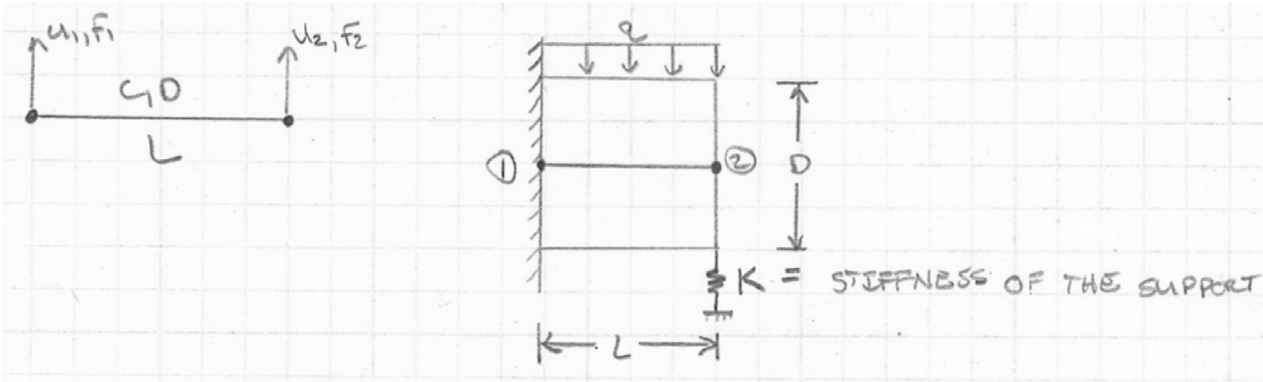
However, a deck is not a beam. Instead of using A and G, use G_a and D.

$G_a = Shear\ stiffness\ (Shear\ force/depth)$
$D = Length\ of\ deck\ along\ the\ primary\ structure\ (depth)$

$$K = \frac{G_a D}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} = K = \mathrm{C}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} =$$

$C = G_a * (D/L\ Ratio) = \ Diaphragm\ stiffness\ (lb/in)$

For the case of supports only at the end of the deck:



$$\begin{bmatrix} C & -C \\ -C & C+K \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} = \begin{Bmatrix} \frac{qL}{2} \\ \frac{qL}{2} \end{Bmatrix}$$

$q = Traction\ line\ load\ on\ deck\ (force/length)$

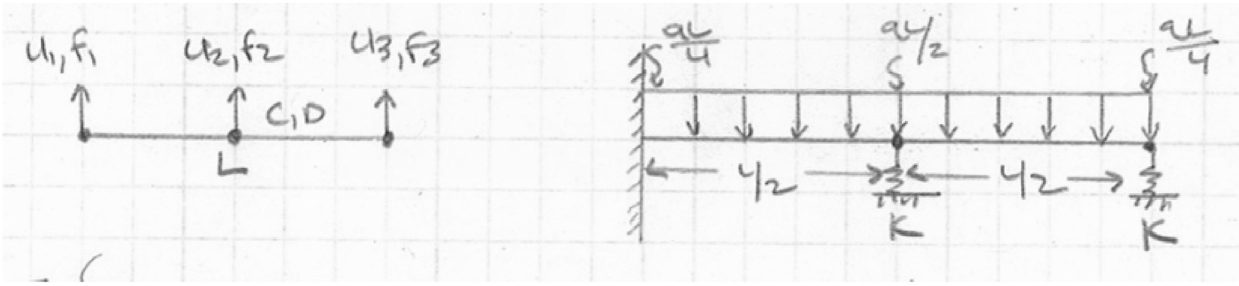
Node 1 is constrained, so the equation becomes:

$$(C+K)u_2 = \frac{qL}{2}$$

$$u_2 = \frac{qL}{2(C+K)}$$

$$\boldsymbol{P_f = Ku_2 = \frac{qL}{2}\left(\frac{K}{C+K}\right)}$$

For the case of supports at end and midspan:



$$\begin{bmatrix} 2C & -2C & 0 \\ -2C & 4C+K & -2C \\ 0 & -2C & 2C+K \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} \frac{qL}{4} \\ \frac{qL}{2} \\ \frac{qL}{4} \end{Bmatrix}$$

Node 1 is constrained, so the equation becomes:

$$[A]\{x\} = \{b\} \ \rightarrow \ \begin{bmatrix} 4C+K & -2C \\ -2C & 2C+K \end{bmatrix} \begin{Bmatrix} u_2 \\ u_3 \end{Bmatrix} = \begin{Bmatrix} \frac{qL}{2} \\ \frac{qL}{4} \end{Bmatrix}$$

$$\{x\} = [A]^{-1}\{b\} = [A]\backslash\{b\} =$$

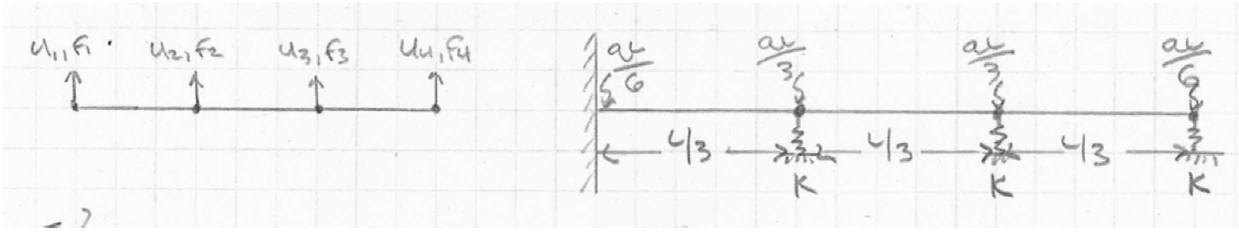
$$u_2 = \frac{qL*(3C+K)}{2K^2+12CK+8C^2}$$

$$u_3 = \frac{qL*(8C+K)}{4K^2+24CK+16C^2}$$

$$\boldsymbol{P_{f1} = Ku_2 = \frac{KqL*(3C+K)}{2K^2+12CK+8C^2}}$$

$$\boldsymbol{P_{f2} = Ku_3 = \frac{KqL*(8C+K)}{4K^2+24CK+16C^2}}$$

For the case where supports are at third points:



$$\begin{bmatrix} 3C & -3C & 0 & 0 \\ -3C & 6C & -3C & 0 \\ 0 & -3C & 6C+K & -3C \\ 0 & 0 & -3C & 3C+K \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{Bmatrix} = \begin{Bmatrix} \frac{qL}{6} \\ \frac{qL}{3} \\ \frac{qL}{3} \\ \frac{qL}{6} \end{Bmatrix}$$

Node 1 is constrained, so the equation becomes:

$$[A]\{x\} = \{b\} \;\rightarrow\; \begin{bmatrix} 6C & -3C & 0 \\ -3C & 6C+K & -3C \\ 0 & -3C & 3C+K \end{bmatrix} \begin{Bmatrix} u_2 \\ u_3 \\ u_4 \end{Bmatrix} = \begin{Bmatrix} \frac{qL}{34} \\ \frac{qL}{3} \\ \frac{qL}{6} \end{Bmatrix}$$

$$\{x\} = [A]^{-1}\{b\} = [A]\backslash\{b\} =$$

$$u_2 = \frac{qL * (45C^2 + 24CK + 2K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}$$

$$u_3 = \frac{qL * (72C^2 + 27CK + 2K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}$$

$$u_4 = \frac{qL * (81C^2 + 18CK + K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}$$

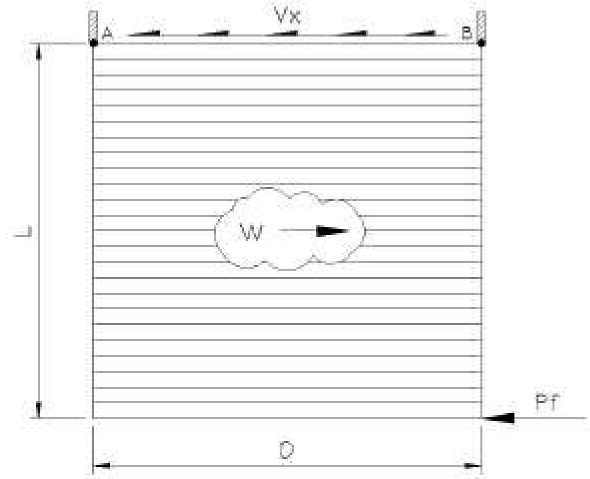
$$\boldsymbol{P_{f1} = Ku_2 = \frac{KqL * (45C^2 + 24CK + 2K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}}$$

$$\boldsymbol{P_{f2} = Ku_3 = \frac{KqL * (72C^2 + 27CK + 2K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}}$$

$$\boldsymbol{P_{f3} = Ku_4 = \frac{KqL * (81C^2 + 18CK + K^2)}{6(27C^3 + 54C^2K + 15CK^2 + K^3)}}$$

APPENDIX E: HAND CALCS - EXCEL SPREADSHEET EXAMPLE

HORIZONTAL DECKBOARD ORIENTATION:



ASSUMPTIONS:

61	Substructure Stiffness, K (lb/in)
12	Length, L (ft)
12	Depth, D (ft)
1:1	Aspect Ratio

SOLUTION:

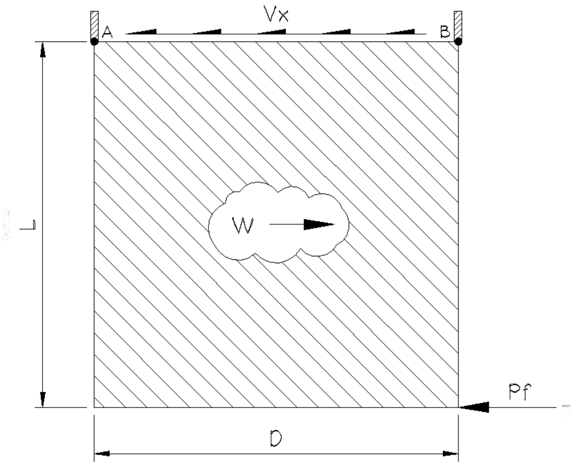
G_a =	1500	lb/in	[Apparent shear modulus of diaphragm, AWC SDPWS 2008, Table 4.3D]
C =	1500	lb/in	[shear stiffness of diaphragm, adjusted by aspect ratio]
C_k =	3.93		[Dynamic Amplification Factor, LaFave 2014]
w = (4 psf)*C_k =	15.7	psf	[Lateral Occupancy Design Load, LaFave 2014]
q = w*L =	189	lb/ft	[Traction Line Load on the deck]
P_f = (qL/2)*(K/(C*(D/L)+K)) =	**44**	**lb**	[Reaction Force of Substructure]
A_y =	**1088**	**lb**	[Tension Force in Hold-Down A]
B_y =	**1088**	**lb**	[Compression Force in Hold-Down B]
v_x =	**185**	**lb/ft**	[Unit Shear in Ledger]

ALLOWABLE CHECK:

v_x = 185 lb/ft > 70 lb/ft NO GOOD [AWC SDPWS 2008, Table 4.3D]

Figure E.1: Spreadsheet for example problem shown in appendix D, horizontal deck boards.

DIAGONAL DECKBOARD ORIENTATION:



ASSUMPTIONS:

61	Substructure Stiffness, K (lb/in)
12	Length, L (ft)
12	Depth, D (ft)
1:1	Aspect Ratio

SOLUTION:

G_a =	6000	lb/in	[Apparent shear modulus of diaphragm, AWC SDPWS 2008, Table 4.3D]
C =	6000	lb/in	[shear stiffness of diaphragm, adjusted by aspect ratio]
C_k =	1.06		[Dynamic Amplification Factor, LaFave 2014]
w = (4 psf)*C_k =	4.2	psf	[Lateral Occupancy Design Load, LaFave 2014]
q = w*L =	51	lb/ft	[Traction Line Load on the deck]
P_f = (qD/2)*(K/(C*(L/D)+K)) =	**3**	**lb**	[Reaction Force of Substructure]

A_y =	**302**	**lb**	[Tension Force in Hold-Down A]
B_y =	**302**	**lb**	[Compression Force in Hold-Down B]
v_x =	**51**	**lb/ft**	[Unit Shear in Ledger]

ALLOWABLE CHECK:

v_x =	51	lb/ft	≤	420	lb/ft	OKAY	[AWC SDPWS 2008, Table 4.3D]

Figure E.2: Spreadsheet for example problem shown in appendix D, diagonal deck boards.