- Sum the shear force resultants of all the elements, including any beam elements, times the distance from the shear center of the cross-section to get the net torsional force.
- Determine the equivalent normal forces and lines of action for all shell and/or solid elements from the extracted normal stresses and the geometric properties.
- Sum the normal forces on the cross-section to get the net axial force.
- Sum the moments from the equivalent normal forces times their distance from the centroid of the cross-section in both the major-axis and minor-axis planes along with any major-axis or minor-axis moments from beam elements to get the net major-axis and minor-axis moments on the cross-section. Note that if there is no net axial force on the cross-section, the moments can be summed about any arbitrary convenient point on the section, such as the neutral axis.

While this procedure can be time consuming when compared with extracting the force effects of lower order elements, the end result is that the shell elements can produce results which can be used for design in a form similar to those produced by beam elements. *Care must be taken to ensure that the coordinate axes of the slice are set-up properly and are understood prior to using the program output. Performing a simplified test case which can be checked by hand is always recommended*. For instance, Section 9.1.2.3.3 demonstrates a check of the moment/shear/axial force slicing capability of an FEA program.

8.2.2 Non-Composite Construction

Many concrete slab on girder highway bridges are non-composite for some, although typically not all, of the applied loads. Examples of non-composite loads would be the girder and deck weight of a bridge with an unshored cast-in-place concrete deck.

Non-composite girder loadings are relatively simple to model and design. The model force effects are based on the stiffnesses of the girders and diaphragms/cross-frames, and the design applies these force effects to the properties of the girder-only section. For 1D or 2D models, the design shears, moments and axial forces can be directly obtained. For 3D models, the design forces would need to be integrated as detailed in Section 8.2.1 before designing the girders according to AASHTO LRFD.

8.2.3 Composite Construction

When a composite section is loaded in bending, the axial stress in the deck is a maximum directly above the girder and then decreases as you move transversely away from the girder centerline due to shear lag. In calculating design capacity of composite sections, a simplification is usually employed. A notional "effective width" of deck is assigned, and the stress on this notional width is assumed to be uniform and equal to the maximum stress in the deck. The effective width of this uniform maximum stress is equal to the width required such that the total force is equal to the sum total force carried over the actual width of participating deck.

For refined analyses, knowledge of the effective width of deck is often not necessary and to some extent may be misleading. What is required for design is a calculation of the moment and shear (and possibly axial force) present in the composite girder. In order to determine these force effects, the forces in the deck in the refined analysis must be proportioned correctly to each composite girder.

In situations where the analyst wishes to determine the effects of shear lag, such as the distribution of normal stresses in the deck, it is important that the mesh is sufficiently refined. A minimum of two elements between web lines is required to capture shear lag effects, but at least four elements is recommended.

When using a slicing utility of an FEA program that automatically integrates the stresses over the selected elements and returns the equivalent beam forces (M, V, P, T), something akin to an "effective width," referred to here as "participating width," must be employed in order to proportionally distribute the deck forces correctly among the girders. Often this participating width is simply halfway to the next girder, or the width that results in no net axial force in the composite section. Quantifying shear lag effects and identifying the participating width in more complicated situations can be a more difficult proposition.

A method to approximate an effective flange width for design purposes is provided in AASHTO LRFD Article 4.6.2.6 for various types of systems (concrete decks, box beams, orthotropic decks, etc.). In multi-girder bridges, typically the design effective flange width is taken to be equal to the tributary width of deck above the member, and the same participating width can be used for analysis purposes. However in some cases, effective width calculations can become complicated if the bridge geometry is not straight forward. For instance, in cases similar to what is depicted in Figure 138, in which the girders are not the same size, the tributary width assumption of AASHTO LRFD is not valid and its use may result in an unconservative design.

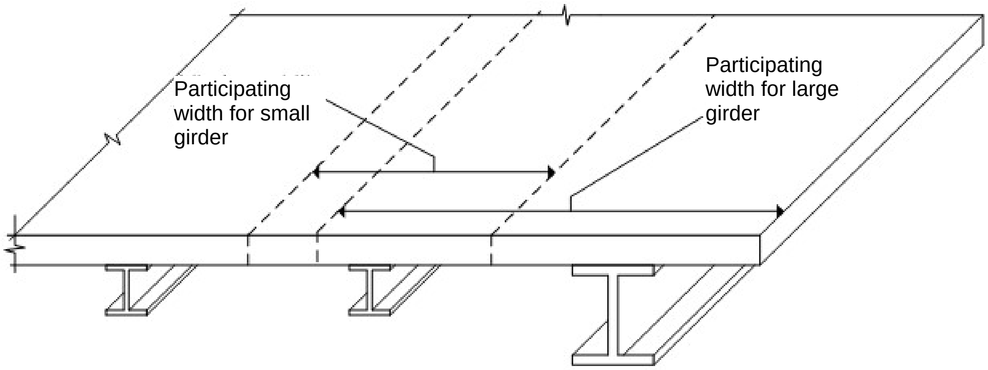

Figure 138. Illustration. Deck system in which the effective flange width set equal to the tributary width may result in an underestimation of force effects for the larger section.

The larger stiffness of the exterior beam will cause a larger width of deck to act compositely with it, so while the tributary width assumption would be conservative for use as a design section for the exterior beam, determining the analysis force effects using this effective width as the participating width would most likely underestimate the actual force effects. In a case such as this, sometimes the refined analysis can be used to determine the participating width which can then also be used as the design "effective width." If the composite girders carry only moment and shear the effective width can be determined by finding the width resulting in no net axial force on the composite section.

One technique for determining the design forces is to integrate the stresses over an estimated participating width of deck slab, then sum the forces over the cross-section, as described in Section 8.2.1 of this manual. By iteratively adjusting the participating width of deck slab until there is no net axial force, the equivalent force effects can be determined. This method also has the advantage of producing a participating width of deck, which can then be used in determining the effective width of deck used for calculating resistance.

When little or no net axial force is present in the composite member, the participating width of deck is not required, and the composite force effects can be determined using the beam forces only. Assuming that the moment in the deck slab is negligible and the axial stress in the deck slab is uniform, the major-axis moment in the cross-section can be determined by adding the moment in the girder section to the moment due to the axial force couple between the deck slab and the girder section. To estimate the moment due to the couple, multiply the axial force in the girder section, which should be equal and opposite the axial force in the effective width of deck, times the arm between the girder centroid and the deck slab centroid.

When net axial forces are present in girders, engineering judgement may be required to determine girder design forces. This may entail estimating the distribution of axial force across the width of the bridge, or bounding the design forces, among the possible approaches.

This method can be used for any model where the beam forces can be isolated from the deck forces, and can also provide a quick check of an FEA slicing utility. The model should account for any Specification required effective modular ratio factors for permanent load effects. This shortcut is not valid when net axial forces are present in the girders, due to transverse bridge loadings or in curved or skewed bridges for instance. Even though the bridge cross-section may not have a net axial force, when individual girders have axial load the stresses must be integrated, unless those effects can be subtracted out prior to calculating the in-plane moment.

Once the equivalent beam force effects (M, V, P, T) have been determined, design can proceed using the AASHTO LRFD Specification as usual. For instance, normal stresses can be calculated using M/S, or shear at the composite interface can be calculated using the well known formula VQ/I as one step in the design of shear connectors for deck slabs. The change in axial force in the girder of a composite section is also equal to the interface shear, and can be used in place of, or as a check on the VQ/I method.

8.2.4 Concrete Girder Bridges

For typical design, per Article 4.5.2.2 of AASHTO LRFD, concrete components are generally modeled using gross (un-cracked) section properties to determine distribution of forces, even though those forces may be used to design a cracked section. Although cracked stiffness properties are seldom used in models for routine slab-girder bridge design, they might be utilized for more complex structures or when more accurate results are required.

As a consequence, the shell element stresses extracted from an analysis model are only valid if the stresses present would not result in cracking or crushing of the concrete. If the analysis shows that cracking occurs, the correct stresses would have to be found by applying the force effects from the model to the design section, accounting for the lack of participation of the cracked concrete in tension as illustrated in Figure 139.