A Comparison of Different Methods to Design Cast-in-Place Concrete Diaphragms for Seismic Load

Rahul Sharma, P.E.
Jeremiah Legrue, S.E.
Doug Hohbach, S.E.
Hohbach-Lewin, Inc.
Palo Alto, CA

Abstract

All three components (horizontal, vertical and foundation) of a building’s lateral force resisting system are important; however, past research and effort has concentrated on the vertical systems rather than the horizontal systems. Recently there has been increased emphasis on diaphragm analysis and design. This paper presents a comparison of different diaphragm design methods that have been promulgated over the past several years. The main focus is the design of collectors, which are used to transfer load from the diaphragm into the vertical elements. Some guidelines, such as NEHRP 2010 and NEHRP 2016, use a flexible diaphragm concept, and thus assume that the collector is the full length of the diaphragm. This is not consistent with the fundamental design assumption that concrete diaphragms are rigid and can lead to large and impractical collectors. Other references such as “Evaluation of Collector Design for Concrete Diaphragms” by J.S. LeGrue utilize rigid diaphragm or partial length methods for collector design. This paper compares and contrasts the above methods and investigates analytic and experimental studies that have been used to validate these methods.

Introduction

While concrete diaphragms are an important part of the seismic force resisting system for most concrete buildings, limited research has been done to understand how these elements will perform in an earthquake. Older textbooks on reinforced concrete such as “Reinforced Concrete Structures” by R. Park and T. Paulay (Park and Paulay, 1975) neglect to mention concrete diaphragms. Traditionally, guidance on how to design concrete diaphragms, has often been simplistic, recommending that they be designed utilizing a uniform shear method and/or that they be designed to always remain elastic.

This paper will focus on the design and analysis of collectors, which are the elements sometimes required to transfer seismic force from the diaphragm into the vertical seismic force resisting elements.

Despite the increased use of computer programs for modelling the seismic response of buildings, collector elements are often excluded from analytical models where the diaphragm is considered rigid or semi-rigid. Therefore, it is necessary to perform diaphragm and collector design separate from the building finite element model.

Traditional collector design is consistent with the assumption of a flexible diaphragm. That is, it assumes that shear is uniformly distributed over the length of the diaphragm, the diaphragm lacks axial stiffness, and stiff collector elements are required to deliver diaphragm forces to the vertical seismic force resisting elements. The diaphragm may be designed for a lower shear demand; however, the use of discrete axial-loaded collector elements constitutes a load path with less redundancy and ductility than a continuous diaphragm loaded in shear. Consequently, building codes such as ASCE 7-10 require that most collector elements be designed to resist amplified seismic forces (ASCE 7-10). Alternative methodologies are utilized in practice to eliminate “unnecessary” collectors and reduce collector demands where collectors are required. Two such alternatives are the rigid diaphragm method and the limited collector length method.

The rigid diaphragm method relies on the stiffness of the diaphragm to distribute diaphragm forces to the vertical seismic force resisting elements. The diaphragm is designed to have sufficient strength to deliver the design force to the vertical elements within the length of the vertical elements.
The limited collector length method is a hybrid approach that utilizes a collector of limited length determined so that diaphragm strengthening is either unnecessary or limited.

This paper provides an overview of relevant past publications on collector design for concrete diaphragms and addresses the basic three collector design approaches, the traditional or uniform shear method, the rigid diaphragm method and the limited collector length method. These methods are compared in the design of a simple example structure and compared with respect to the finite element analyses results for the example structure. Finally, a case study is presented comparing the practicality of the three methods.

Strut and tie analysis, another promising method for determining the load path through the diaphragm to the lateral force resisting elements, can be complicated to apply to seismic design (ATC, 2010). More work is needed before it can be applied in practice, thus this methodology is not addressed in this paper.

![Figure 1 – Reinforcing in Concrete Diagram](image)

**Code Issues**

Diaphragms, chords and collectors are addressed in ASCE 7-10 Section 12.10. Per Section 12.3.1.2 concrete diaphragms are to be idealized as rigid; however, Section 12.10.2 states that “Collector elements shall be provided that are capable of transferring the seismic forces originating in the other portions of the structure to the elements providing the resistance to those forces.” A general interpretation of these two sections is that a well-defined load path must exist through the diaphragm to the lateral force resisting elements. Section 12.10.2.1 requires collectors to be designed for maximum force due to (1) the equivalent lateral force procedure or the modal response procedure multiplied by an overstrength (Ω) factor, (2) the diaphragm design force (from Section 12.10.1.1) multiplied by an overstrength (Ω) factor and (3) the minimum diaphragm design force. These forces do not need to exceed the maximum diaphragm design force. Practically, one must address both the force that comes from the overall building analysis and the force that comes from the maximum acceleration of the story in question (which is not accurately captured by the overall analysis).

Note that ASCE 7-10 explicitly specifies how to determine the magnitude of the diaphragm force, but is vague about how the force is distributed through the diaphragm. Also, there are no code requirements regarding the effective width of a collector.

**Overview of References on Collector Design**

Until about ten years ago there was little published guidance addressing the design of collectors within concrete diaphragms. The 2008 SEAONC Blue Book lists a few acceptable methods such as the uniform shear distribution method, the rigid diaphragm method and strut and tie methodology and concludes that “any mechanism of force delivery can be assumed in analysis provided the complete load path has adequate strength.” (SEAOC, 2008)

The National Council of Structural Engineers Association developed a series of examples that emphasize that the diaphragms should be designed to remain elastic and inelastic deformations should be limited to the vertical elements: “the global ductility system reduction factor, R, that is used to...
reduce the elastic response spectrum demands on the LLRS implies that adequate overstrength is provided in diaphragms, collectors and connections to ensure these remain essentially elastic.” (NCSEA, 2009)

NEHRP acknowledges that “many aspects of diaphragm design are left open to interpretation and engineering judgement.” Full-depth collectors designed by the uniform shear method are briefly described but extensive guidance is provided for the design of partial-depth collectors. Partial-depth or limited length collectors require secondary full-length collectors and additional chord reinforcement. This provides a load path to transfer diaphragm shear, which is assumed uniform across the length of the diaphragm, into the vertical lateral force resisting element. A recommendation is also given, unsupported by any quantitative justification, to always provide at least a 25’ long or one bay length collector. (NEHRP, 2010 and NEHRP, 2016)

ATC 72-1 provides more nuanced recommendations: “Past design practices, such as assuming uniform shear along a collector, can overestimate demands because the assumed load path differs from the actual path” and “The uniform shear method became popular before collector forces were required to be designed with amplified forces. Using this method with amplified forces can make the design of collectors impractical for real buildings.” (ATC, 2010)

LeGrue (2014) addresses three approaches to collector design: the uniform shear, rigid diaphragm and limited collector length methods. Finite element analysis is used to evaluate the performance of each method. It is one of the few sources which analytically validates the design methods.

Collector Design Methods

The three basic hand calculation approaches, the uniform shear method, the rigid diaphragm method and the limited collector length method are described below. Note that the rigid diaphragm and limited collector length methods are generally consistent with a rigid or semi-rigid diaphragm idealization.

**Uniform Shear Method**

The uniform shear method assumes that the diaphragm has finite shear stiffness and zero axial stiffness. Therefore, uniform shear exists across the length of the diaphragm and axially rigid members must be provided to collect the shear into the vertical lateral force resisting elements. The collectors must extend the full length of the diaphragm. Given the total shear in the diaphragm, tension and compression force in the collector can be computed from statics, as shown on Figure 2.

The collector design force and required collector steel area can be calculated as follows. It should be noted that the collector design force is amplified by \( \Omega_0 \) per ASCE 7-10. This requirement was added to the building code due to the observed failures in the 1994 Northridge earthquake.

\[
T_u = \Omega_0 V_u \left( \frac{L_{coll}}{L_{diaph}} \right) \quad \text{(Equation 1)}
\]

\[
A_s = \frac{T_u}{f_y \phi} \quad \text{(Equation 2)}
\]

where \( V_u \) is the shear force along the line of resistance, \( L_{coll} \) and \( L_{diaph} \) are the lengths of the collector and diaphragm, respectively, \( f_y \) is the yield strength of the collector reinforcement and \( \phi = 0.90 \) per ACI 318-14 Table 21.2.1 and Table 21.2.2.

The collector should be detailed in such a way that there is an adequate load path from the diaphragm into the lateral force resisting system. A design example by the Structural Engineers Association of California suggests that collector reinforcement be distributed into the slab, instead of concentrated within the width of lateral force resisting element. This results in an eccentricity, which is accounted for through the creation of local chord elements. (SEAOC, 2008)
Rigid Diaphragm Method

The rigid diaphragm method relies on the axial and shear stiffness of the diaphragm, which is idealized as a rigid body, to transfer seismic load to the vertical lateral force resisting elements. Collectors are not required; instead the diaphragm is strengthened near the lateral force resisting element so that its shear strength ($\phi V_u$) exceeds the diaphragm shear force ($V_u$).

The diaphragm shear strength is checked with Equation 3.

$$\phi V_u = \phi A_{cv} (2\lambda \sqrt{f_c'} + \rho_t f_y)$$  \hspace{1cm} (Equation 3)

where $A_{cv}$ is the wall length times the slab thickness, $\lambda$ is a light-weight concrete factor ($\lambda = 1$ for normal-weight concrete), $f_c'$ is the concrete strength, $\rho_t$ is the ratio of steel shear reinforcement to gross concrete area, $f_y$ is the steel reinforcement yield strength and $\phi = 0.6$ per ACI 318-14 Sec 21.2.4.1. $\rho_t$ is modified until ($\phi V_u > V_u$). ACI 318-14 Sec 18.12.9.2 limits the nominal shear capacity ($V_n$) to $8 A_{cv} \sqrt{f_c'}$.

If an acceptable design cannot be obtained, the slab thickness should be increased.

Limited Collector Length Method

The limited collector length method relies on the stiffness of the diaphragm to transfer force to the lateral force resisting system in a manner similar to the rigid diaphragm method; however, partial-length collectors are used, instead of increasing the diaphragm shear strength, to completely transfer the calculated seismic shear to the lateral force resisting system.

The minimum collector length is determined from Equation 4 and Figure 3.

$$L_{col} = \frac{V_u - lwall (\phi V_u)}{\phi V_n}$$  \hspace{1cm} (Equation 4)

$$\phi V_n = \phi a_{cv} (2\lambda \sqrt{f_c'} + \rho_t f_y)$$  \hspace{1cm} (Equation 5)

$V_u$ is the shear distributed to the shear wall and $\phi V_u$ is calculated by equation 5 where $a_{cv}$ is the area of concrete slab per unit foot and the rest of the terms are defined for Equation 3.

The collector design force can be calculated with the Equation 6. The required steel area is calculated in the same way as it is for the uniform shear method. If $L_{min}$ is less than the length of the lateral force resisting element, no collector is required and the limited collector method reduces to the rigid diaphragm method.

$$T_u = \Omega_0 V_u \left(\frac{L_{col}}{L_{min}}\right)$$  \hspace{1cm} (Equation 6)

Note that for both the rigid diaphragm method and the limited collector length method, that slab reinforcing is required to transfer the shear forces to the slab area adjacent to the vertical lateral force resisting element.
Example Building

The example building used to compare the three methods is one story, rectangular in plan and has a concrete shear wall at each end. To understand how different parameters affect the diaphragm design, the diaphragm length ($L_{\text{diaph}}$), wall location, and diaphragm design force, $F_{px}$, are varied to create eight different configurations. A plan layout of the example building can be seen in Figure 4 and Figure 5, and a description of the different configurations can be seen in Table 1. Diaphragm design parameters are summarized in Table 2.

The building is assumed to be designed and detailed as a special reinforced concrete shear wall building. Thus the response modification factor is $R=5$ and the overstrength factor is $\Omega_0=3.0$. Accidental torsion has been neglected; the diaphragm shear along each line of resistance is $V_u = \frac{F_{px}}{2}$. 

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**Figure 3 – Force Distribution – Limited Collector Length Method**

**Figure 4 – Example Buildings (Plan View)**
Figure 5 – Reinforcement Layout for Example Buildings

<table>
<thead>
<tr>
<th>Label</th>
<th>L_{diaph} (ft)</th>
<th>W_{diaph} (ft)</th>
<th>Wall Location</th>
<th>L_{wall} (ft)</th>
<th>F_{px} (k)</th>
</tr>
</thead>
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<tr>
<td>1A</td>
<td>150</td>
<td>300</td>
<td>Center</td>
<td>25</td>
<td>750</td>
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</tr>
<tr>
<td>4A</td>
<td>75</td>
<td>300</td>
<td>Center</td>
<td>25</td>
<td>1200</td>
</tr>
<tr>
<td>4B</td>
<td>75</td>
<td>300</td>
<td>End</td>
<td>25</td>
<td>1200</td>
</tr>
</tbody>
</table>

Table 1 – Example Building Configurations
Table 2 – Diaphragm Design Parameters

Collector Design Summary

The collector reinforcement for the three studied diaphragm design methods is summarized in Table 3. From the results, it can be seen that the limited collector length method results in the lowest required amount of reinforcement.

<table>
<thead>
<tr>
<th>Collector Design Forces and Reinforcement</th>
</tr>
</thead>
</table>

Finite Element Analysis

Finite element models of the example building configurations were created and analyzed in ETABs. Line elements were used to model the reinforcement and shell elements were used to model the concrete slab. The diaphragm design force, $F_{ps}$, was amplified by the response modification factor and applied as a smeared surface load on the diaphragm.

Cracking was accounted for through an iterative process. The analysis was run and the tension stress in each slab element was checked and compared to the concrete’s tension stress capacity (assumed equal to the modulus of rupture (ACI, 2014)). If the concrete tension stress capacity was exceeded, that slab element was removed from the model and the analysis was repeated. This process continued until all remaining slab elements had tensile stress less than their capacity. The maximum stress demand-to-capacity ratios for the different example buildings can be seen in Table 4. The collector reinforcement for the uniform shear method and the limited collector length method are modeled such that a portion of the required reinforcement is concentrated within the width of the wall and the rest is distributed into the slab. The maximum stress ratios are given for the distributed reinforcement ($F_{sd}$), concentrated reinforcement ($F_{sc}$), concrete compression ($C_c$) and concrete shear ($V_c$). These values should be compared to the response modification factor $R=5$ since the diaphragm design force was amplified by the same factor.

<table>
<thead>
<tr>
<th>Table 3 – Collector Design Forces and Reinforcement</th>
</tr>
</thead>
</table>

Diaphragm thickness, $t$  | 10 in |
Diaphragm reinforcement ratio, $\rho_t$  | 0.00194 (#5 @ 16 in o.c.) |
Specified concrete strength, $f_{c}^s$  | 4000 psi |
Concrete shear strength, $2\sqrt{f_{c}^s}$  | 126 psi |
Concrete tension strength, $7.5\sqrt{f_{c}^s}$  | 474 psi |
Concrete compressive strength, $0.85f_{c}^s$  | 3400 psi |
Reinforcing steel strength, $f_y$  | 60000 psi |

<table>
<thead>
<tr>
<th>Flexible Diaphragm</th>
<th>Rigid Diaphragm</th>
<th>Limited Collector Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_s$ (in²)</td>
<td>$A_t$ (in²)</td>
<td>$Wgt.$ (lbs)</td>
</tr>
<tr>
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<td>$T_s$ (k)</td>
<td>$A_t$ (in²)</td>
</tr>
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<td>1B</td>
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<td>2B</td>
<td>1250</td>
<td>23.6</td>
</tr>
<tr>
<td>3A</td>
<td>313</td>
<td>6.0</td>
</tr>
<tr>
<td>3B</td>
<td>625</td>
<td>11.9</td>
</tr>
<tr>
<td>4A</td>
<td>500</td>
<td>9.5</td>
</tr>
<tr>
<td>4B</td>
<td>1000</td>
<td>18.8</td>
</tr>
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</table>
From these stress ratios, it can be seen that all three design methods perform acceptably. The steel stress ratios for the uniform shear method are often less than the response modification factor which shows that this method is conservative. The steel stress ratio for the rigid diaphragm method varies from 1.7 to 5.5 for the different example buildings. The main cause for this variation is the location of the wall along the depth of the diaphragm. Steel stress ratios vary from 1.1 to 2.2 for walls placed mid-depth of the diaphragm and vary from 5.0 to 5.5 for walls placed at the edge of the diaphragm. The steel stress ratios for the limited collector length method are similar to the rigid diaphragm method, but generally lower by 10% to 15%.

<table>
<thead>
<tr>
<th>Label</th>
<th>( F_{ed} )</th>
<th>( F_{ec} )</th>
<th>( C_i )</th>
<th>( V_i )</th>
<th>( F_{ed} )</th>
<th>( F_{ec} )</th>
<th>( C_i )</th>
<th>( V_i )</th>
<th>( F_{ed} )</th>
<th>( F_{ec} )</th>
<th>( C_i )</th>
<th>( V_i )</th>
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<tbody>
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<td>1.9</td>
<td>N/A</td>
<td>0.2</td>
<td>1.7</td>
<td>Same as rigid diaphragm</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1B</td>
<td>1.2</td>
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<td>2.7</td>
<td>N/A</td>
<td>5.4</td>
<td>N/A</td>
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<td>Same as rigid diaphragm</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2A</td>
<td>0.7</td>
<td>1.2</td>
<td>2.1</td>
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<td>2.2</td>
<td>2.2</td>
<td>0.9</td>
<td>0.4</td>
<td>2.4</td>
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</tr>
<tr>
<td>2B</td>
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<td>2.2</td>
<td>4.0</td>
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<td>5.5</td>
<td>N/A</td>
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<td>0.9</td>
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<td>Same as rigid diaphragm</td>
<td></td>
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<tr>
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<td>2.8</td>
<td>N/A</td>
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<td>Same as rigid diaphragm</td>
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<tr>
<td>4A</td>
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<td>5.1</td>
<td>2.3</td>
<td>N/A</td>
<td>4.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Demand-to-Capacity Ratios

Case Study

A case study of a building located in an area of high seismicity is presented to compare the results of designing to the three methodologies presented above. The case study building is one of four residential and retail buildings over a two level concrete podium. The lateral force resisting system consists of concrete floor diaphragms and special reinforced concrete shear walls. A plan of the building is shown in Figure 6. The collector for the wall of interest (also shown in Figure 6 and 7) will be designed using the uniform shear, rigid diaphragm and limited collector length methods.

Figure 6 – Case Study Diaphragm (Plan View)
This case study will investigate the first floor of the building. The floor diaphragm is 7.5” thick and has typical bottom reinforcement of #4 at 24” on center. The concrete strength is 5,000 psi and the steel reinforcement grade is 60,000 psi. From an ETABs analysis, the diaphragm design force which needs to be collected into the wall is 414 kips (this value does not include $\Omega_0$). The wall length is 16'-3". The total length of the diaphragm, including the wall length, is 211’.

**Uniform Shear Method**

The collector for the wall is designed using the uniform shear diaphragm method.

First, the diaphragm shear demand is calculated in Equation 7 and it can be seen to be much lower than the diaphragm capacity (calculated in Equation 8). The overstrength factor, $\Omega_0$, is not used to calculate the diaphragm shear.

$$v_{u,Diaphragm} = \frac{414 \text{ kips}}{212'} = 1.95 \text{ klf} \quad \text{(Equation 7)}$$

$$\phi v_n = (0.6)(7.5''*12''/ft)(2 \times 1.0 \times \sqrt{5000 \text{ psi}} + 0.0011 \times 60,000 \text{ psi}) \times \left(\frac{1 \text{ kip}}{1000 \text{ lb}}\right) = 11.2 \text{ klf} \quad \text{(Equation 8)}$$

$$\phi v_n > v_{u,Diaphragm} \quad \text{(Equation 9)}$$

The diaphragm shear capacity without the $\phi$ factor is compared to $8A_{cv}\sqrt{f'_c}$, which is the diaphragm shear capacity limit.

$$v_n = \frac{11.2 \text{ klf}}{0.6} = 18.7 \text{ klf} \quad \text{(Equation 10)}$$

$$8A_{cv}\sqrt{f'_c} = (8)(7.5' \times 12 \text{ in/ft}) \times \frac{1 \text{ kip}}{1000 \text{ lb}} = 50.9 \text{ klf} \quad \text{(Equation 11)}$$

$$v_n < 8A_{cv}\sqrt{f'_c} \quad \text{(Equation 12)}$$

The design force in the collector can be found using statics and is shown in Figure 8.

The maximum tension or compression force in the collector is 255 kips, which can be seen in Figure 8. Using this, the required collector steel can be obtained

$$A_s = \frac{2.5 \times 382 \text{ kips}}{0.9 \times 60 \text{ ksi}} = 17.7 \text{ in}^2 \quad \text{(Equation 13)}$$

The required area of steel would correspond to (18) #9 bars. The amount of steel in the collector could be reduced along its length and the final collector reinforcement is shown in figure 9. The collector reinforcement is reduced at 1/3 and 2/3 of its length. The collector reinforcement is extended its development length past the point where it is needed.
For this case study, the collector will be detailed as a slab collector. If the bars are spaced at 8” o.c., the collector would have a width of 11’-4”. In order to avoid confining the collectors, the collector width would have to be large enough so that the concrete stress is less than 0.2 f'c', which per ACI 318-14 Section 18.12.7.5 is the trigger for requiring collector ties. This will require a collector width of at least 10’-7”. #5 bars spaced the 16” o.c. will be placed transverse to the collector bars to transfer seismic load from the collectors in the slab to the wall through shear friction. Additional chord bars also would be placed transverse to the collector bars to resist the moment due to the eccentricity of the collector reinforcement and the shear wall. These were not calculated for this design example, however.

**Rigid Diaphragm Method**

The rigid diaphragm method is used next to evaluate the load transfer from the diaphragm to the shear wall. The shear demand on the different walls is calculated below.

\[
v_{u,Wall} = \frac{414 \text{ kips}}{16.25 \text{ ft}} = 25.5 \text{ klf} \quad \text{(Equation 14)}
\]

The typical diaphragm reinforcement of #4 @ 24” o.c. was calculated previously and is shown again below. Since the diaphragm shear capacity with the typical podium diaphragm reinforcement is less than the diaphragm shear demand, additional reinforcement will need to be added.

\[
\phi v_n = 11.2 \text{ klf} \quad \text{(Equation 15)}
\]

\[
\phi v_n > v_{u,Diaphragm} \quad \text{(Equation 16)}
\]

In order to satisfy the diaphragm demand, the diaphragm reinforcement needs to be increased to #4 @ 4”. The new diaphragm capacity is calculated in Equation 17. This value is compared to the diaphragm limit.

\[
\phi v_n = (0.6)(7.5" \times 12" / \text{ft}) (2 \times 1.0 \times \sqrt{5000 \text{ psi} + 0.0065 \times 60,000 \text{ psi}}) \times \left(\frac{1 \text{ kip}}{1000 \text{ lb}}\right) = 28.7 \text{ klf} \quad \text{(Equation 17)}
\]

\[
\phi v_n > v_{u,Wall} \quad \text{(Equation 18)}
\]

\[
v_n = \frac{28.7 \text{ klf}}{0.6} = 47.8 \text{ klf} \quad \text{(Equation 19)}
\]

\[
8A_{cv} \sqrt{f'_c} = 50.9 \text{ klf} \quad \text{(Equation 20)}
\]

\[
v_n < 8A_{cv} \sqrt{f'_c} \quad \text{(Equation 21)}
\]

The diaphragm reinforcement is increased only in the region shown in Figure 10 for the rigid diaphragm method. This area was calculated by determining where the diaphragm demand reduced to the diaphragm capacity as shown in Figure 10.

**Limited Collector Length Method**

The collector designed according to the limited collector length method can be found using statics. The collector, unlike the uniform shear method, does not need to extend the full length of the diaphragm.

A required collector length of 21’ is found from Equation 22.
\[ L_{\text{col}} = \frac{414 \text{ kips} - 16.25' \times 11.2 \text{ klf}}{11.2 \text{ klf}} \]
\[ = \frac{232 \text{ kips}}{11.2 \text{ klf}} = 20.7' \approx 21' \]  
(Equation 22)

\[ A_s = \frac{2.5 \times 232 \text{ kips}}{0.9 \times 60 \text{ ksi}} = 10.7 \text{ in}^2 \]  
(Equation 23)

The required area of steel would correspond to (11) #9 bars. Since the collector only extends 21', the reinforcement is not reduced along the collector length, however it could be as described in the uniform shear method section.

Discussion on Results

The volume and weight of the additional steel reinforcement from the different methods is presented in Table 5. The steel reinforcement due to shear friction ties and reinforcement used to resist the eccentric collector moment was not accounted for in the table. From Table 5, it can be seen that the limited collector length method is the most efficient with respect to reinforcing steel weight. The uniform shear method produces a design which weighs approximately 7½ as much as the rigid diaphragm method and 9 times as much as the limited collector method.

Table 5 – Design Weight Comparison

<table>
<thead>
<tr>
<th></th>
<th>Uniform Shear Method</th>
<th>Rigid Diaphragm Method</th>
<th>Limited Collector Length Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume in (^3)</td>
<td>33,264</td>
<td>9,314</td>
<td>NA</td>
</tr>
<tr>
<td>Weight lbs</td>
<td>9,314</td>
<td>3,663</td>
<td>1,026</td>
</tr>
<tr>
<td>As (^2)</td>
<td>1.231</td>
<td>1.231</td>
<td>1.026</td>
</tr>
</tbody>
</table>

The uniform shear method produces a conservative design for which in multiple locations the steel stress capacity demand ratios do not exceed half of the acceptable values, but at the critical locations for the end wall case, was just at the acceptable design value.

The rigid diaphragm method produced designs with steel stress ratios very close to the acceptable design values.

The limited collector length method produced equivalent steel stress capacity demand ratios at the critical locations as the uniform shear method, but with less assumed length of collectors and less reinforcing steel, and is thus recommended.

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