1-Way Concrete Floor Systems

Modern Methods in Structural Analysis

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Introduction

The fundamental method of analysis and design of concrete beam-girder and column systems has changed very little in the past few decades. The standard practice of idealizing the floor system as a set of single beam lines for analysis and design has been successfully used on nearly every concrete building of this kind in the US for many years. This article suggests that this current methodology is lacking in several areas, and a more appropriate 3D floor analysis would offer the following advantages.

Analytical Accuracy

A full three dimensional floor model can effectively consider the interaction that exists between various beam and girder lines in the structure. Sometimes unexpected or unintended behaviors are identified in a 3D analysis that could easily be overlooked in the more traditional approach. These behaviors include the effect of member support displacements, span loading influence on parallel spans on the forces of the floor beams, girders and columns.

Data Management

The simplicity of a single beam line analysis could also be construed as its weakness. The advantages of a 3D model extend well beyond the analytical results. The error prone process of manually entering member geometry, loading and boundary conditions into a number of spreadsheets or programs to get the analysis and design of all the individual beam lines in a structure is very costly. The expense of engineering and production time on a concrete structure, relative to steel, is one of the main reasons an engineer may choose the competing material for design and construction.

Contemporary Single Beam Line Analysis Method

There are a number of tools that are used in the analysis of concrete beam lines. The following describes the steps typically taken in this approach.

1. Identify the structural geometry for the beam line including beam, column and slab dimensions. In some cases the stiffness of the members are not reduced.

2. Identify support conditions including column stiffness above and below the beam line and knife-edge (pinned) supports for girders.

3. Identify all loading on each span of the beam line. In the case of girders, which may be supporting other beam lines, the engineer will need to design the supported beam lines first. Another option is to calculate tributary areas to estimate the loads on the girder from the supported beams.

4. Generate the appropriate finite element model.

5. Add the beam end moments from the lateral analysis to the beam line model for all lateral members. In most cases, the lateral model was defined with cracked sections for the beams and columns per ACI 318-99 Section 10.11, which will produce a model that is not as stiff as the single beam line model that is used for the gravity load analysis of the beam.

6. Once the skip loading has been defined and the analysis performed, the results are used to design the reinforcement. In most cases, the analysis results may need to be transferred to another spreadsheet or program to finalize the design, especially when the members are part of intermediate or special moment frames.

7. The data management for column design and drawing production, which typically follows, is extensive and is dependant on the completion of the beam line designs.

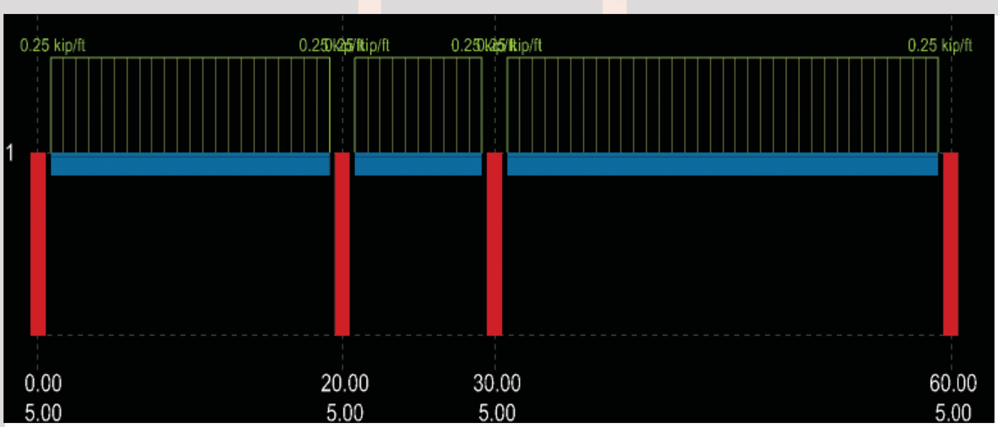

Figure 1 – Typical model of a 2D beam line. For beam lines supported by girders the model would use knife-edge (pinned) supports rather than the columns shown above. In some case the columns above the floor would also be modeled.

Figure 2 – Plan view of single beam line analysis with no support displacements

Figure 3 – Plan view of beam line1 analyzed as part of a full 3D model with proper support displacements and rotations. Notice that the beam line has smaller negative moment at interior supports and non-zero moments at the ends due to the rotational stiffness of the supporting girders.

Analytical Accuracy

The most common methodology employed in the analysis of beam-girder floor systems in the US is the single beam line method. This method typically consists of dividing a floor's framing into single strips, then analyzing and designing each 'strip' independently (and grouping similar strips for productivity). By choosing to analyze the strips independently, the engineer is making certain assumptions about the behavior of the floor and the interaction of the various beam lines that may not be valid. In fact, as suggested in this section, there are many situations where the strip method may not produce acceptably accurate analytical results.

Support Displacements

Current strip method design approach involves taking a single beam line out of a floor system and modeling it in a 2D frame analysis *(Figure 1)*. In this approach, the affect of the support stiffness must be considered on the analytical model or a significant inaccuracy in the design forces is observed. In the examples below, a beam line that is supported on girders is modeled using fixed vertical supports *(Figure 2)* and then modeled using a more accurate 3D analysis that automatically accounts for the girder and column vertical stiffness *(Figure 3)*. As is observed, there is significant difference in the forces produced by these two approaches. Additionally, with the strip method there is often grouping of the analysis results for similar strips. However, as shown in *Figure 4* for a single bay containing 3 joist lines, the analysis forces vary (possibly significantly) for the joist support ends as they extend from edge of the bay to the center of the bay, all due to the variation of the support flexibility at the girder. To calculate the vertical stiffness variation along the length of a girder for consideration in the analysis of each joist line would be prohibitively expensive, but required to get the more appropriate analytical results.

Figure 4 - As can be seen 3 parallel beam lines will have nearly at 10% different in design moments due to their location on the supporting girders

Influence Area of Beam Loading

In a single beam line analysis the effect that loading one beam line has on other beam lines in the structure is ignored.

As shown in Figure 5, in some cases the loading on a single beam line will produce unexpected moments in the surrounding framing. This is a very good example of how considering the continuity across the whole floor rather than just on a single beam line can significantly impact the final analysis results that are used for design.

The result of a more complete account of the skip loading of members across the full floor produces final moment diagrams that have the negative moment envelope extending farther into the span and the positive moment envelops extending closer to the supports. In most cases the difference is not significant, but in other cases it may require the top reinforcement to be extended beyond the standard 0.3 or 0.33 times the length of the span as seen in *Figure 6* & *Figure 7*.

Member Stiffness Influence

An example of the impact of the bending stiffness used in the modeling of the structure can be seen in the following figures. *Figure 8* and *Figure 9* show the bay between grids 1-2 and C-D from *Figure 10*. *Figure 8* is a plan view of the 3D model using the bending stiffness reduction values from ACI 318-99 Sect 10.11, except for beam line 3 which uses the full uncracked bending stiffness. Similarly, *Figure 9* is a plan view of the same model but using 2D analysis of the beam lines with knife edge supports. Beam lines 3 and 5 have the same stiffness in both models. As can be seen from the two figures, the 2D model is not very sensitive to the beam bending stiffness. The 3D model is much more sensitive to the difference in stiffness. The 3D model shows the significant effects of the relative stiffness of the beams, girders and columns in the structure.

Given the reduction in peak negative moment at the ends of the spans due to the proper modeling of member stiffness and consideration of the support displacements, it is likely that moment redistribution will not need to be considered.

The first thing that one will notice when checking the torsion on a 3D model is that a significant number of girders will now require torsion reinforcement, where it may not have been considered previously. There are two reasons for this. The first is that most engineers do not check torsion on interior girders, because they fail to consider the situation where only the beams framing into one side of the girder are loaded with live load. The second reason is that, in reality, the girder is often analyzed using an unrealistically high torsional stiffness. A number of references [2,3,4] indicate that the torsional stiffness should be reduced by at least 70% and in some cases a full 100% reduction is suggested. In effect, by using a knife edge support in the single beam line model, the engineer is taking the torsional stiffness of the supporting girder to be zero (i.e, a 100% reduction in the girder torsional stiffness).

Unfortunately, the ACI 318-99 code does not directly address the issue of torsional reduction but does provide leeway for the engineer to use their judgment.

Reducing the torsional stiffness of the members may seem unrealistic, but on farther study can be justified for a number of reasons. Once the member cracks in torsion, it loses a significant amount of its torsional capacity which it cannot recover once the loading has been removed. Another reason is that as long as the analysis and design are consistent, the reduction in torsion on a girder means that the beams that it is supporting will take that torsional load as flexure. The advantage of the 3D model in this case is that the engineer does not need to do anything special to account for the issues related to relative member stiffness (torsion and flexure). They are automatically taken care of through the analysis. Finally, it should be noted that in nearly all cases when girders are designed as a 2-D frame, they are in effect assumed to have 100% reduction in torsional capacity.

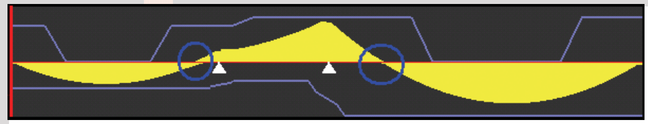

Figure 6 - Design moment envelope for a 2D beam line1 model

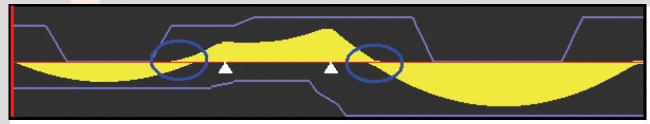

Figure 7 - Design moment envelope for a 3D model. As you can see the beam line1 positive and negative moment regions extend beyond the 2D model results

Data Management

The advantages of a full 3D model on the accuracy, not only of the analysis but also the design and construction document development, should also be considered. Done correctly there can be significant increases in the accuracy and productivity (efficiency) of the analysis, design and drawing development when working with a single 3D model.

There are a multitude of steps to designing a single beam line on a floor. The problems of bookkeeping and tracking design changes as the structure evolves during the engineering process can become quite a large part of the engineer's work.

The ability to combine any of these tasks and to have one integrated model can significantly reduce the potential errors that can be introduced into the design as data is transferred from one analysis or design tool to another. Also, reducing the effort required to design concrete building structures will in turn make the material much more attractive to structural engineers when compared to steel. Obviously, some buildings need to be built in steel and some need to

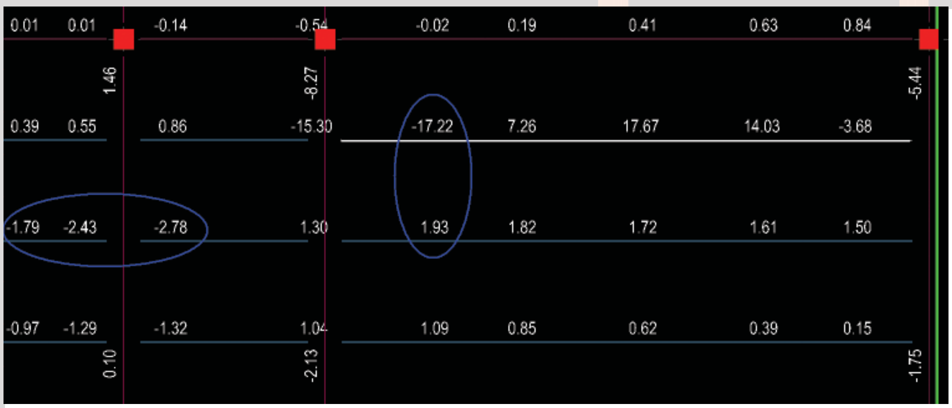

Figure 5 - An example of how the loading of only the white colored beam can impact adjacent beam lines in other bays.

As an example, look at beam line 11 in *Figure 10*. The torsion on the girder between grids 1 and 2 is 25kip-ft at 0% torsional stiffness reduction, 4.3 kip-ft at 90% reduction and 0.35 kip-ft at 99% reduction. For the 18x12 beam section, the unreinforced torsional capacity (ϕTu) is calculated to be approximately 3.5kip-ft. So, depending on the assumption of the girder torsional stiffness, the girder may or may not need torsional reinforcement.

Torsion in Beams

There are several situations in which torsion on a beam may be overlooked in the single beam line approach. One example is where beams that frame on either side of a girder may be slightly offset similar to that shown for the framing of beam line 11 between grid 2 and 3 in *Figure 10*. Due to the offset framing on either side of the top girder in beam line 11, even at 99% torsional stiffness reduction, the maximum torsion is still 4.3 kip-ft, which will require torsional reinforcement. In 2D analysis models there is a possibility of missing the torsion problem in situations like this.

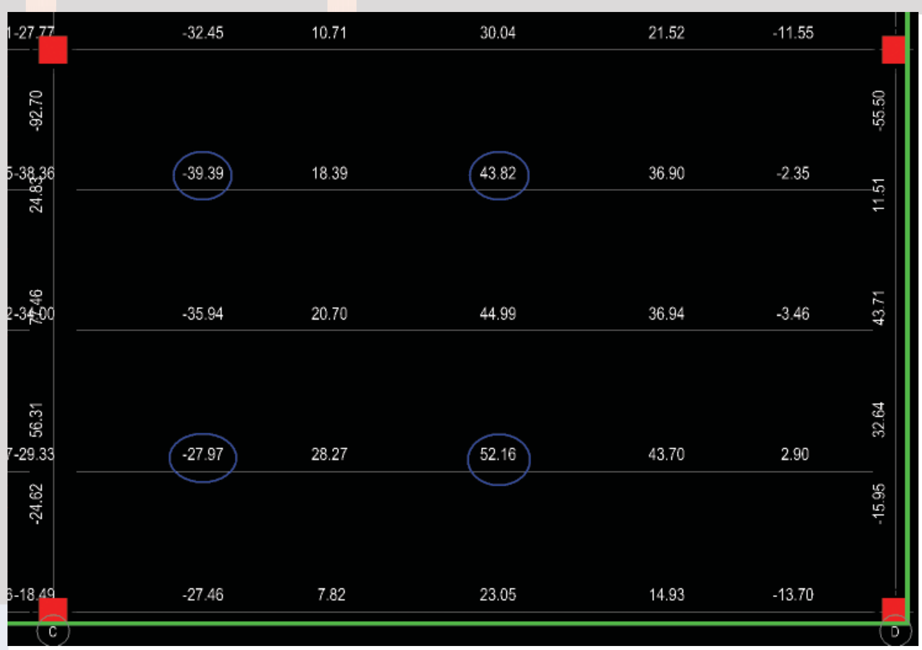

Figure 8 - Moment at quarter points of beams in a 3D model. Beam line 3 is using no reduction in bending stiffness. Beam line 5 is using 0.35 times member bending stiffness. The results indicate the analysis can be sensitive to the cracked bending section used in a 3D model.

be built in concrete. For the buildings that can be built in either material, the decisive factor may be the engineer's or the construction manager's preference.

Conclusion

Given the accuracy of a 3D model, when compared to a number of individual single beam line analyses, there are some questions that may come to mind.

Why don't engineers use 3D models to analyze the full floor system?

Up until recently, there have been very few if any tools that will easily let the engineer model the floor system, automatically generate the live load skipping and then provide the results in a simple and concise way so it can be used for design. Another reason is that the engineering community has been using the single beam line analysis method for a long time and they have made the process as efficient as possible, so they are comfortable with it.

Figure 9 - These are the same spans as Figure 8 and modeled as 2D beam lines. As you can see the difference in stiffness between beam line 3 and 5 has very little impact on the final moments.

Why don't more buildings fail if things like beam torsion, moment and shear envelops may be unconservative?

In most cases, the credit goes to two of the pillars of engineering - conservative design and structural redundancy. The other reason is that, to a large extent, the engineer defines the failure mechanism of the structure and designs for it. The real problem is that because the floor is not analyzed and designed as a single system, the engineer may overlook problems that are caused by unusual, and sometimes typical, framing.

Why bother to create a 3D model if the methods we currently have are safe and familiar to the engineer?

The reason to use a 3D model is related to the three main issues that are addressed in this article.

1. The 3D model will give a much more realistic picture of the interaction of the individual beam lines on the rest of the floor. Torsion can be accounted for properly, and the shear and moment required capacity envelopes can be more comprehensive.

2. The method produces a consistent model that properly considers the loading and stiffness of the gravity and lateral systems, without any special effort on the engineer's part.

3. The work required in modeling, analyzing, designing, detailing and tracking changes can be significantly reduced by combining a number of the individual steps that are currently required when using single beam line models.▪

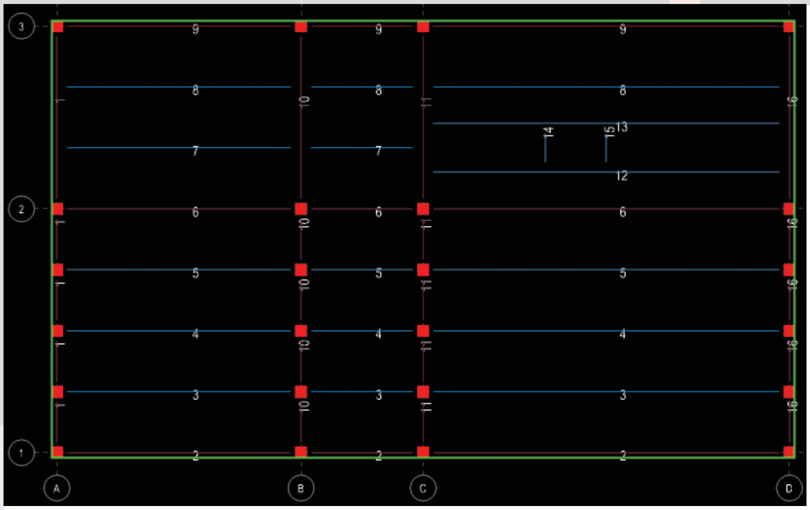

Figure 10 - Floor plan of structure with uneven bay widths. Beam line numbers are shown.

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[2] "Hormigón Armado" (Spanish), Motoya, Meseguer and Moran, 12th Edition, Ed. Gili, Madrid-Spain, 1988

The authors mention that the structure will behave exactly in the same way as it was idealized in the analysis (cracked or uncracked). They suggest modeling the reinforced concrete structures with a very low torsion rigidity i.e. assume it is significantly cracked.

[3] "Reinforced Concrete Fundamentals, 4th ed.", Ferguson, John Wiley, 1979.

The author indicates that while flexural stiffness decreases maybe 50 percent from cracking, torsional stiffness drops down to 5 or 10 percent its uncracked value. The author also mentioned that the consideration of the torque to be used in the design is very complex due to the cracking effect. Thus it is always better to neglect the rigidity of the members for torsion and to consider them fully cracked.

[4] "Reinforced Concrete Structures", Park and Paulay, John Wiley, 1975.

The authors indicate for most situations the assumption of zero torsional stiffness can be made. They do indicate that it is still important to provide at minimum torsion reinforcing to prevent excessive service load cracking.