Investigation into Excessive Deflections in a Concrete Flat Slab

Senior Project Fall 2021

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Architectural Engineering

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Introduction: Project Background and Purpose

This senior project was inspired by a project experience during a summer internship in Denver, Colorado at Wiss, Janney, Elstner Associates, Inc. After a pipe froze and burst in the 13,000 sq. ft. basement of a two story building built in the 1990's, an investigation was needed to determine the structural impacts of the event. A site visit was performed to collect data, and it quickly became clear that slab deflections and strength were top priorities. The slab was able to deflect in the basement due to a cardboard void form that was used to accommodate expansive soils. This project will discuss the site visit techniques used to determine areas of concern, an in-depth analysis and discussion of techniques used to accurately predict long-term deflections in flat slabs, and load testing philosophy addressing concerns about slab strength.

Flood Event

The cause of the flooding was a water based fire suppression line that froze during the winter months. Upon freezing, the water in the pipes expanded and ultimately caused them to burst. It was reported by the property manager that water had accumulated up to a depth of 8-10 ft. At that depth with 13,000 sq. ft. in plan, there would be over 1.25 Olympic-size swimming pools worth of water sitting on the slab.

The flooding event could have been avoided altogether had there been a dry pipe sprinkler system in place rather than a wet pipe sprinkler system. The difference between the two systems is that a wet pipe sprinkler system sits idly with water in the pipes, while a dry pipe system sits idly with compressed gas in the pipes. When a fire occurs, the dry pipe system uses mechanical equipment to open a valve, allowing water from an insulated tank to shoot through the pipes and ultimately extinguish the fire. The dry pipe system will typically be more expensive, but it ends up being worth the additional cost in cases like this where a flood could have been avoided. Figure 1 shows a dry pipe system on the right and a wet pipe system on the left.

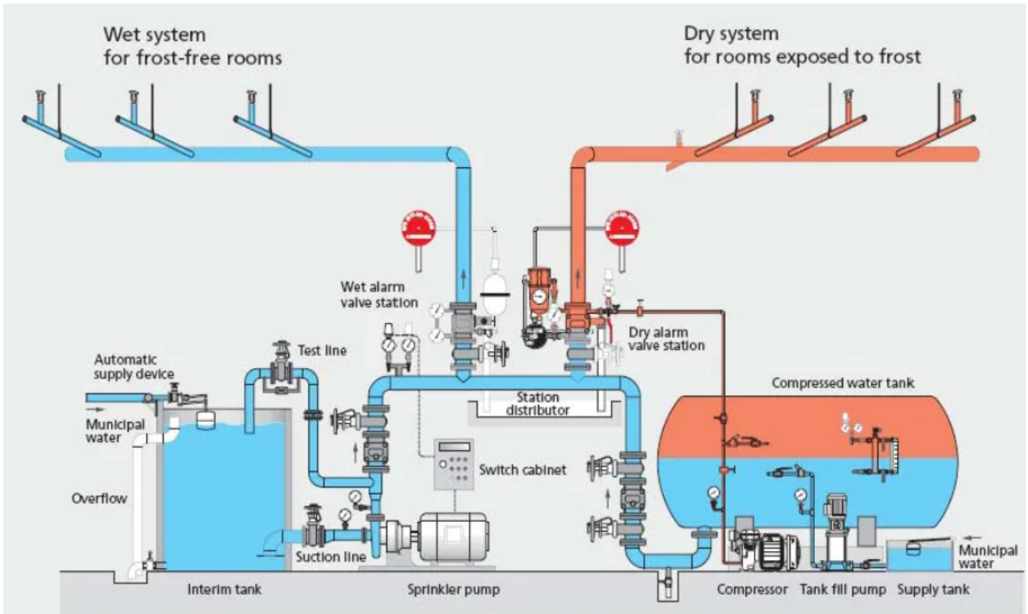


Figure 1 [1]

Site Visit

Upon visiting the site, the first priority was to determine the true height of the flood. It was reported that the flood was 8-10 ft., although this was important to confirm as every additional foot of water adds 62.4 psf. of loading. A water stain line in the sheathing of the elevator shaft served as the best marker for the true flood height. It was measured inside that elevator shaft that the true height of the flood was actually between 5 and 6 ft. as seen in Figure 2, which greatly reduces the load.

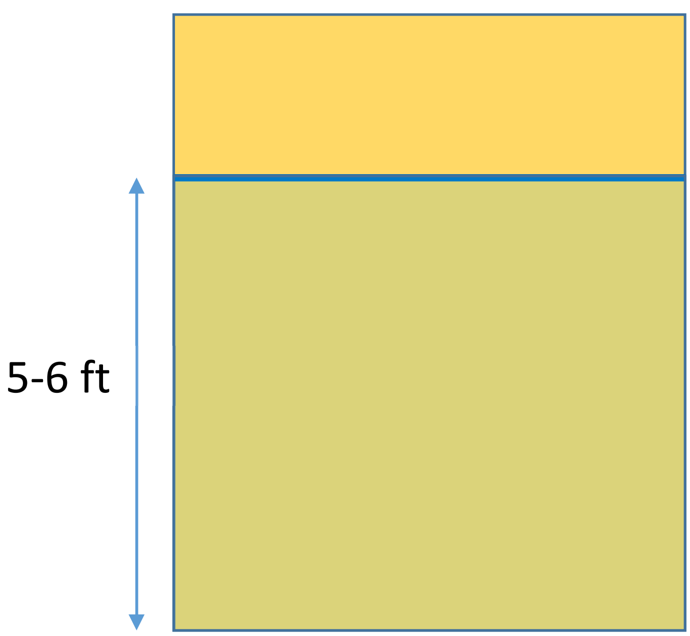


Figure 2

The next item that was investigated during the site visit was the cracks in the concrete. Cracks were discovered mainly in areas of tension in the top surface of the slab, where the slab is experiencing negative moments. These cracks were clean and sharp, which indicates that they are likely new. Had they been dull and dirty, it would be more difficult to say with confidence that the cracks were due to the flood event. However, given their condition, they are likely associated with the flood. The crack widths reached up to 1/16 in. which is not extreme, but definitely something that needs to be taken seriously. There was concentrated cracking around the columns lined up with the foundational support piers as can be seen in Figure 4.

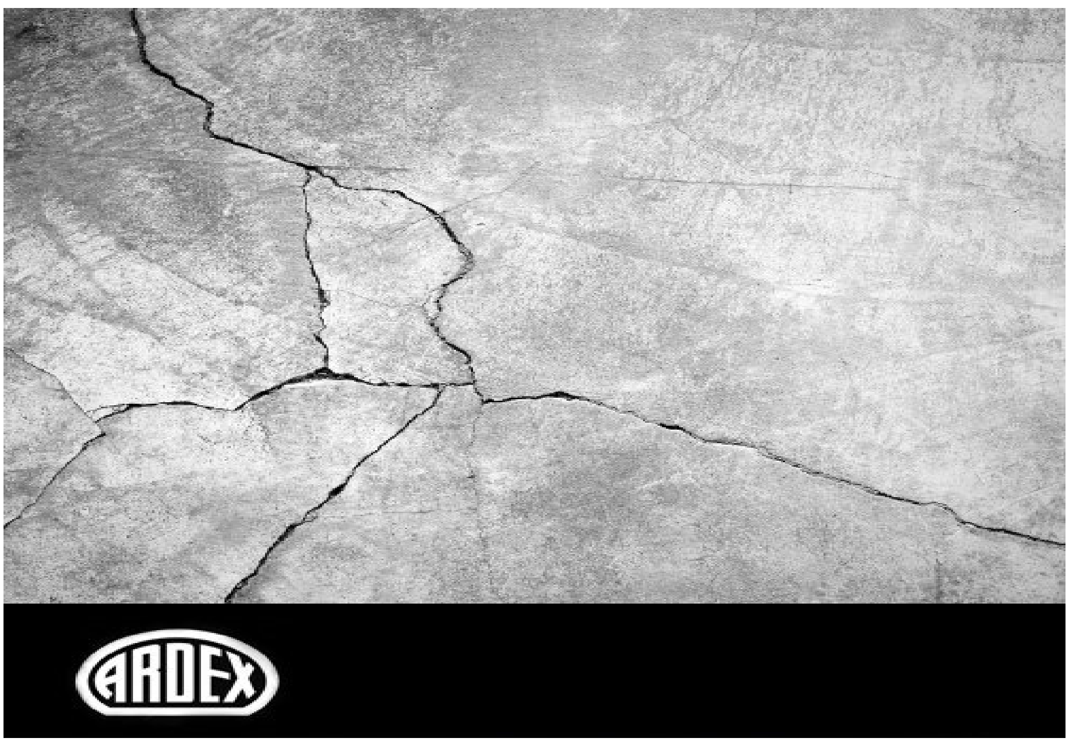


Figure 3 [2]

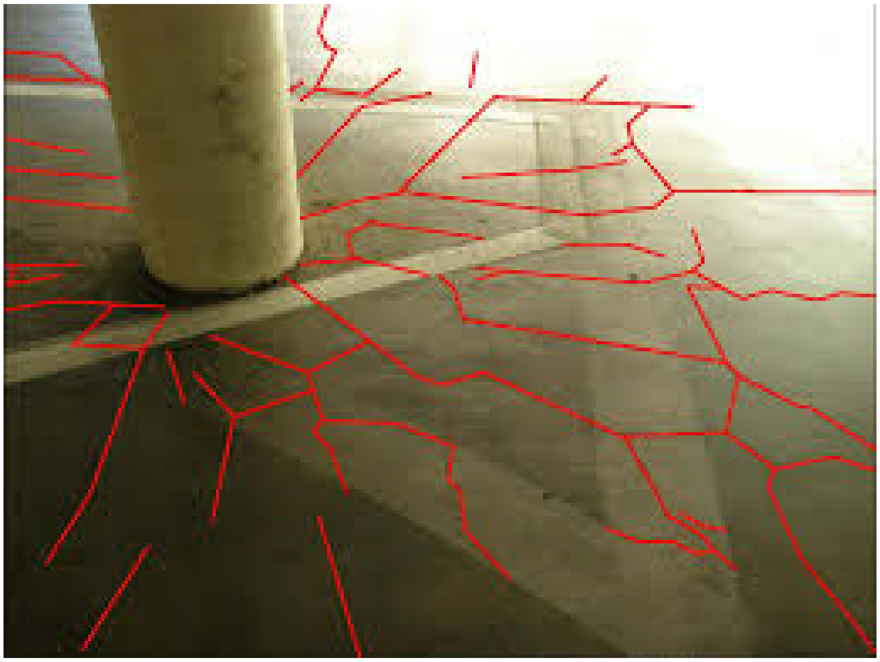


Figure 4 [3]

One of the more concerning things found during the site visit was discovered when looking inside of a cutout in the slab that was made to facilitate plumbing repairs. The thickness was measured inside the cutout. The slab was originally specified to be 13 in. thick by the design engineer. However, inside the slab cutout, the range of thickness was between 10.5 in. and 12.25 in.

Figure 5 [4]

The last task to complete during the site visit was a relative elevation survey. This was completed with a zip level which has an accuracy of +-1/8 in. The maximum deflection that was found was 1-5/8 in. as can be seen in Figure 6.

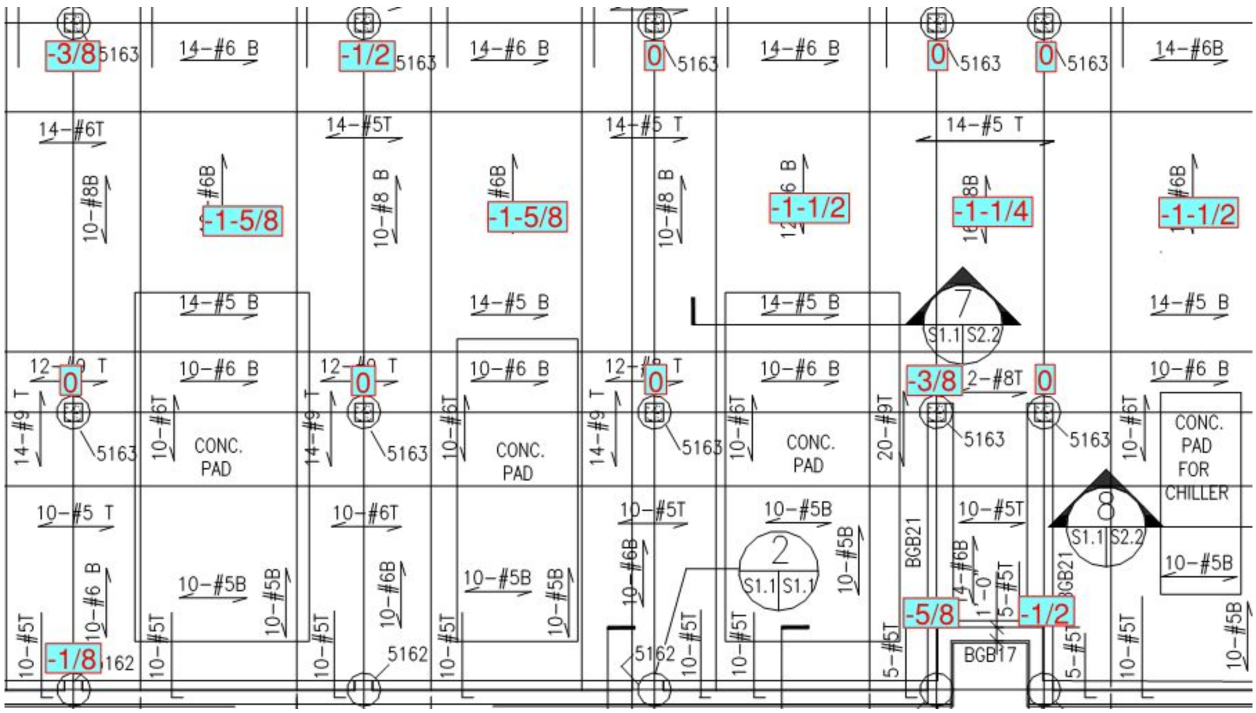


Figure 6

After the site visit, there were essentially 3 main concerns. The first is punching shear as indicated by the cracking around the columns. This cracking could be indicative of the initiation of punching shear which is a violent failure that is to be avoided at all costs. However, that is outside the scope of this project which will focus on slab deflection and strength. The deflection is definitely a concern. At 29 ft. in length and 1-5/8 in. deflection, that is equal to L/214. This can be deemed excessive and should be analyzed. Secondly, strength must be investigated to see if there are any concerns of failure in the future due to a loss of strength.

Deflections

In order to determine if deflections could be accurately predicted as measured based on the ACI code, the slab was first modeled using spSlab. spSlab is a software made by StructurePoint that utilizes the equivalent frame method in order to model one-way and two-way slabs. The equivalent frame method models a 3 dimensional structure as a series of 2 dimensional frames centered on the support lines, which is the columns in this case. This will result in a frame that has a column strip down the middle and a half middle strip on both outer edges as seen

in Figure 7. This must be done twice in the case of the slab being analyzed because the reinforcement is different in the x-direction and the y-direction. Figure 8 shows the x-direction analysis line outlined in green, and the y-direction analysis line outlined in red.

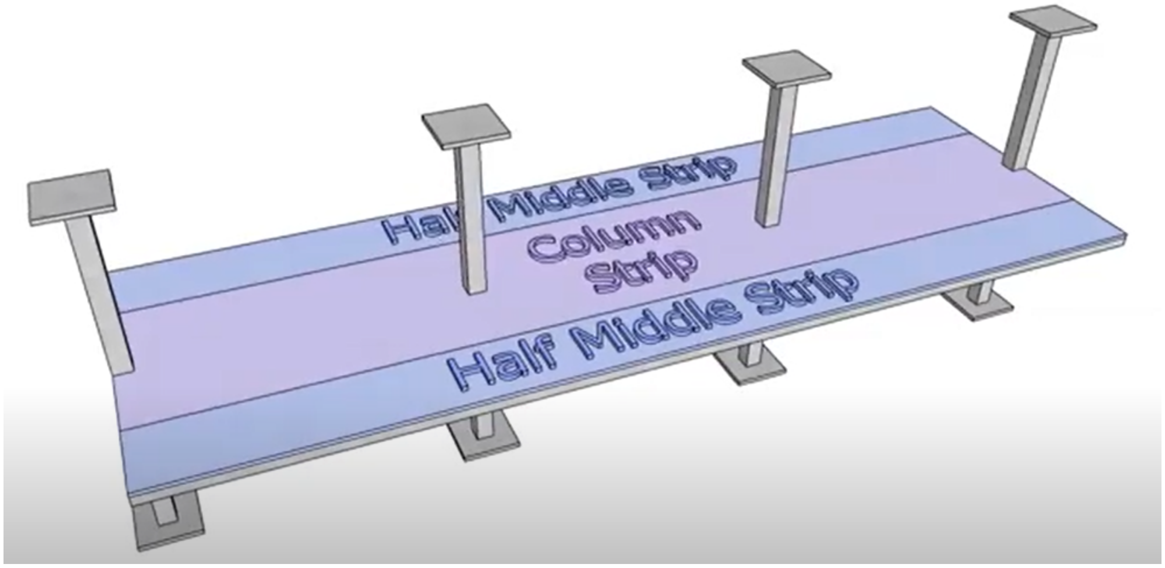


Figure 7 [5]

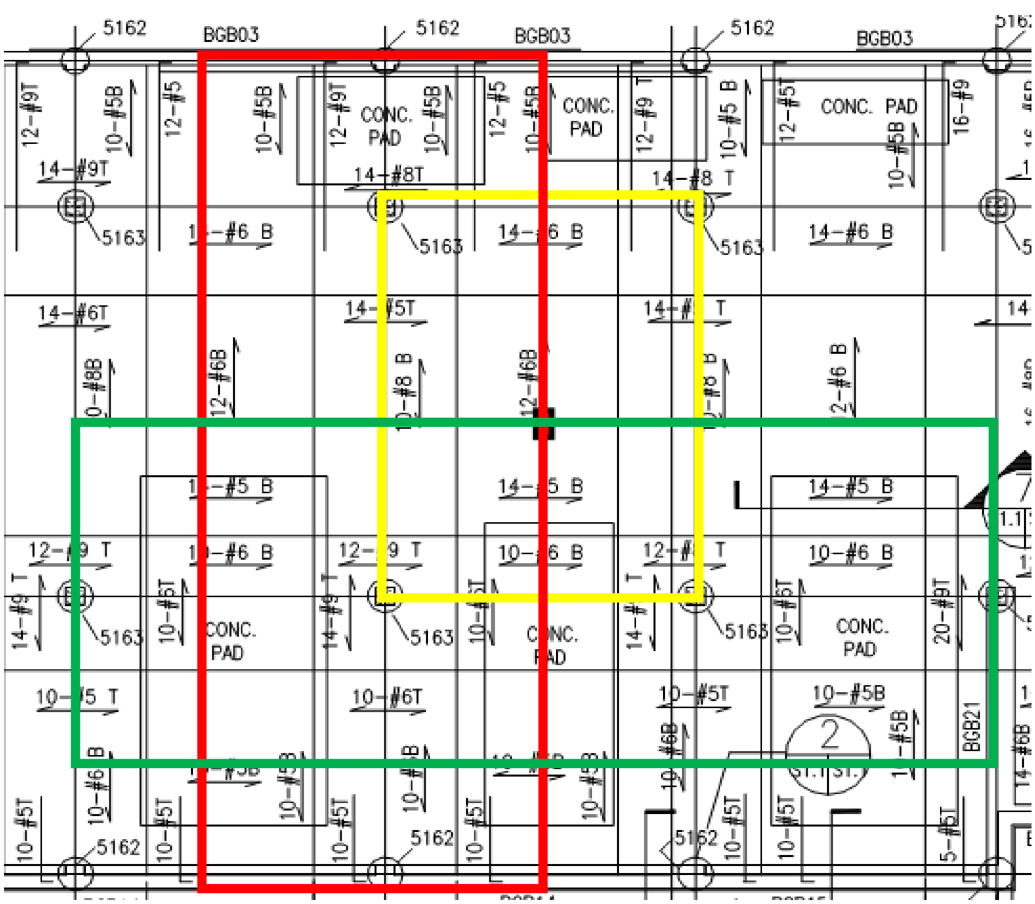


Figure 8

After modeling the slab in both directions using spSlab, the deflection at midspan is then calculated using the combined bending equation seen at the top of Figure 9. This value being calculated is the maximum instantaneous deflection that the slab experiences during the flooding event.

$$\Delta = \frac{\left(\Delta_{cy} + \Delta_{mx}\right) + \left(\Delta_{my} + \Delta_{cx}\right)}{2}$$

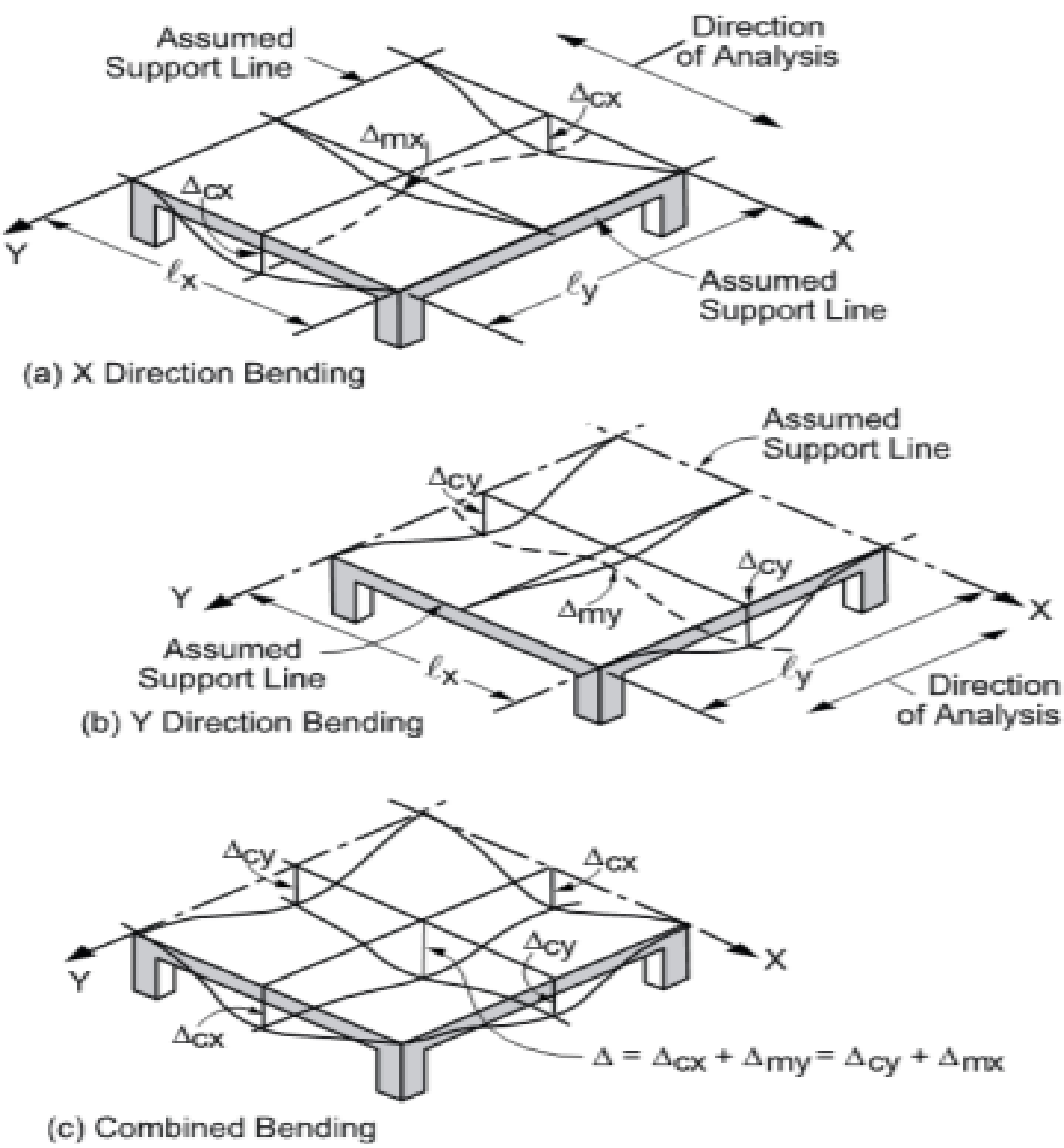


Figure 9 [6]

In order to calculate long term deflections, it is necessary to first find the instantaneous deflection due to dead load and sustained live load. In order to find this deflection, it is not enough to simply put in those loads and find the deflection. That is because the section is likely cracked during the flood, and the software would not have any way of knowing that the stiffness is reduced. Rather, it is more logical to find the deflection with the total load, and then backtrack by a ratio of the total static moment due to dead load and sustained live load divided by the total static moment due to the entire load including the flood. This is illustrated in Figure 10.

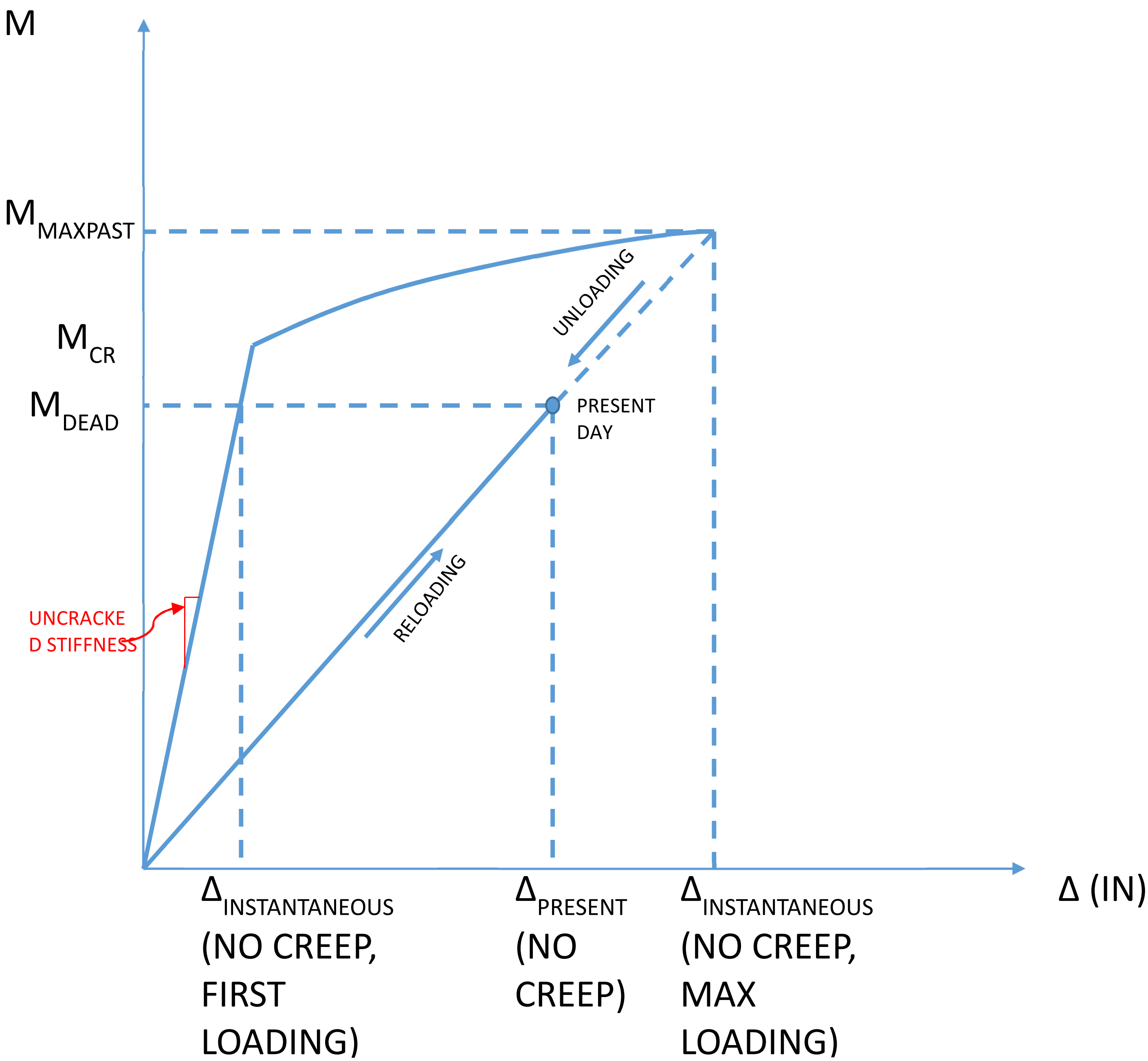


Figure 10

The moments that are being brought into the graph above are the total static moments coming out of spSlab. The total static moment is basically the difference between the maximum positive moment and the average of the two negative moments. Figure 11 illustrates the total static moment.

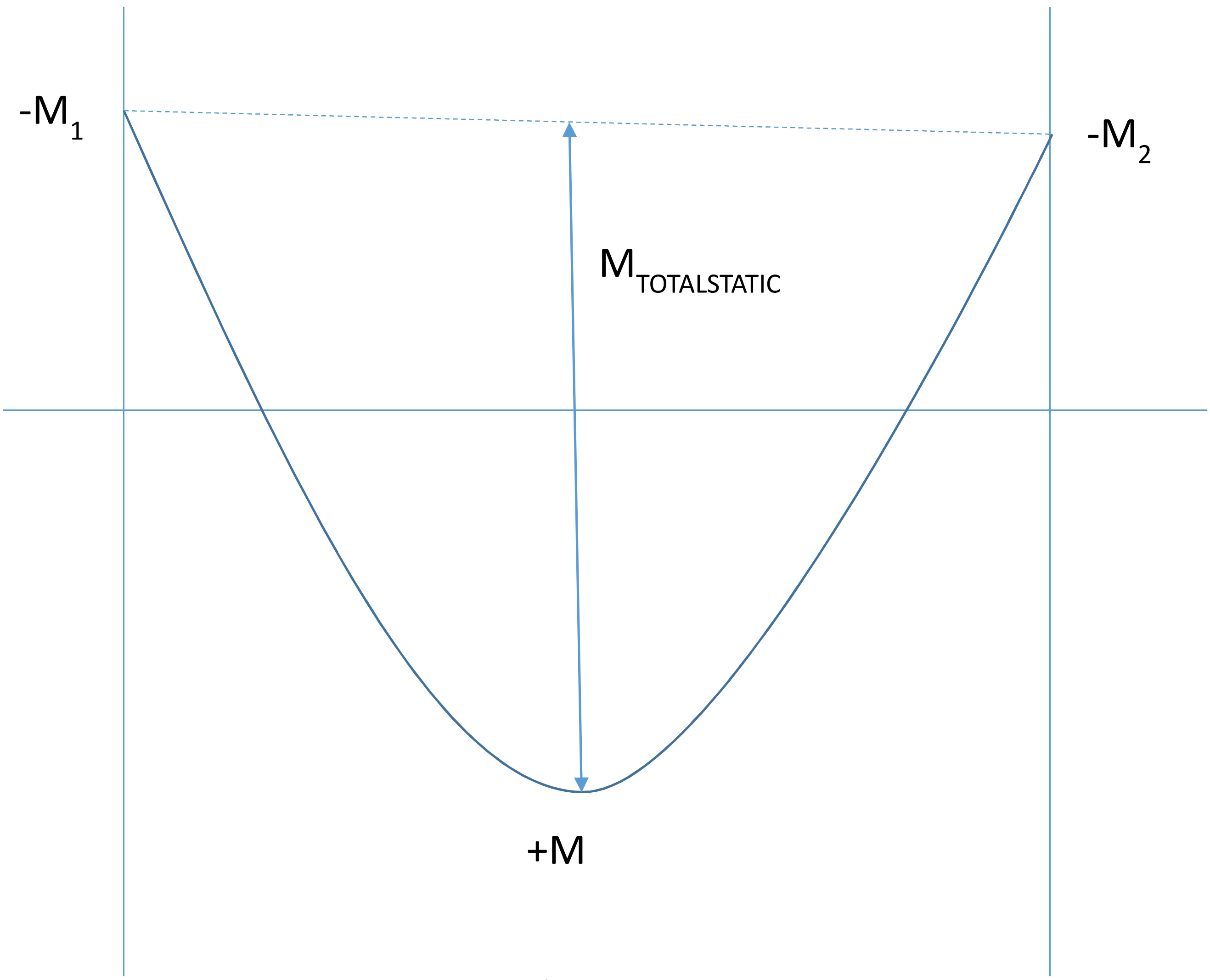


Figure 11

Once the instantaneous deflection due to dead and sustained live load has been found, it must be multiplied by a long term multiplier, λ_Δ, to find the long term deflection. This multiplier is supposed to take into account creep and shrinkage. Creep is the property of concrete that it will deflect over time under service loading. Shrinkage is cracking and internal stress in concrete that occurs due to volume change as moisture is lost in the concrete. Both of these factors play a role

in increasing the long term deflections. ACI 318-19 uses a time dependent factor in order to determine the long term multiplier. Basically, the longer the member has been in place, the more it will deflect. Figure 12 and Figure 13 along with the equation below show how to calculate λ_Δ.

$$\lambda_\Delta = \frac{\xi}{1 + 50\rho'}$$

Sustained load duration, months	Time-dependent factor ξ
3	1.0
6	1.2
12	1.4
60 or more	2.0

Figure 12 [7]

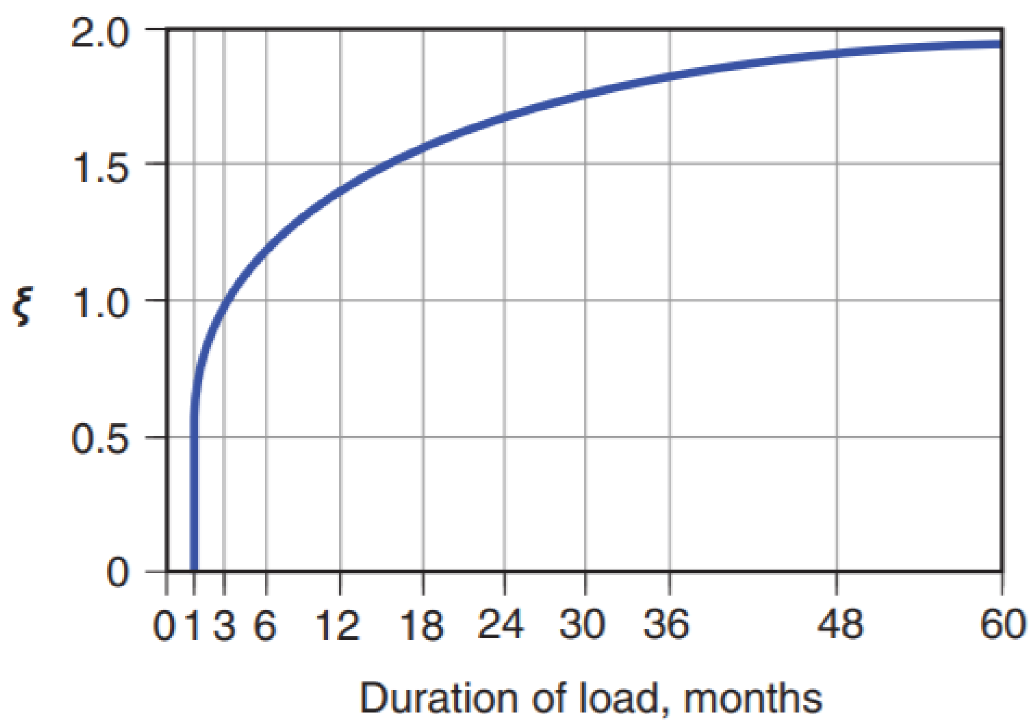


Figure 13 [7]

A calculation finding the permanent deflection using ACI 318-19 methods can be found in Appendix A. The results of this calculation show that there should be 0.45 in. of permanent deflection, which is only 30% of the actual deflection measured in the field.

Because the ACI predicts such low deflections, a parametric study was conducted to see how manipulating different variables can change the deflection that is measured. The modulus of rupture, the creep factor, and the shrinkage factor were all treated independently to see how closely the different combinations can predict the deflections. In Appendix B the suggestions by various authors about how to manipulate these factors are tabulated and the results are plotted. For the slab as designed, the closest any of the suggestions got was 0.94 in., or 62% of the real deflection.

It was clearly necessary to make more changes to the calculation in order to accurately predict the deflections. The calculation was run again with all of the same author suggestions, although the next time it was ran the slab thickness was reduced. Since the slab cutout showed a thickness range of 10.5 – 12.25 in., 11.25 in. was used since that is near the average. That is a reduction from the initial analysis which considered the slab to be 13 in. as it was designed. Making that last change caused the deflection to jump to 1.41 in. or 93% of the real deflection. Considering the amount of variables contributing to this calculation, that is a decently accurate final result, and it can be said the deflections are not outrageous and can be justified. Appendix B shows all of these deflections tabulated as well as graphed.

Strength

Strength concerns were addressed through the load testing philosophy. ACI 318-19 allows structural members or systems in existing buildings to be proven code compliant if they can handle a certain amount of load that is greater than the design loads. This is done in a calculated way that is not exactly the same as the flood but the same principles apply. The load combinations to be used in a load test can be seen in Figure 14. At just 6 ft. of water, the total load imposed on the slab is equal to 347 psf. which is greater than any of the load combinations shown could reach.

$$\text{(a) } T_t = 1.0D_w + 1.1D_s + 1.6L + 0.5(L_r \text{ or } S \text{ or } R) \quad (27.4.6.2a)$$

$$\text{(b) } T_t = 1.0D_w + 1.1D_s + 1.0L + 1.6(L_r \text{ or } S \text{ or } R) \quad (27.4.6.2b)$$

$$\text{(c) } T_t = 1.3(D_w + D_s) \quad (27.4.6.2c)$$

Figure 14 [7]

Since none of the members showed any spalling, crushing, or any other significant indications of failure, it essentially passed the load test and proved it is capable of safely handling service loading. The ACI does say that there cannot be cracking indicating imminent shear failure. The slab did show initiation of punching shear. However, this does not mean that shear failure was imminent and it is reasonable to say that the slab was not on the verge of this type of failure.

Conclusion

After a large flood in a building's basement, there were concerns about excessive deflections in the slab as well as the strength of the slab. It was proven that although the deflections were excessive, they were justifiable when looking deeper into the issue. A large takeaway from this is that the ACI code is unconservative when it comes to predicting slab deflections. This is something that engineers must be on the lookout for when designing and repairing slabs. As for strength, the slab was deemed to be at low risk of failure under service loading. That is because of the load testing philosophy which basically states that if a slab can handle loads greater than what it experiences at service level, then the slab must be able to handle loads at service level as well.

Project Impacts

The societal impact of deflections in two-way slab systems, or any slab system for that matter, has to do with the expectations of those interacting with the building. Society holds expectations beyond what the code currently provides. Many people may naturally assume that structural engineers will be able to design slab systems with accurate predictions of deflections, and they will not be satisfied if they come to find out that the actual deflections are in excess of that prediction.

However, as has been proven, codified methods will not necessarily deliver accurate slab deflections. In turn, the question naturally reverts to figuring out who is responsible. Many would say it is the committees who are tasked with writing the code, as it is their methods being used that are resulting in less accurate slab deflections. However, the committees' goal is not simply to find the right deflections. It is to come up with methods of design that will result in serviceable structures. Those two are different, as the former often requires in-depth analyses, and the latter allows for methods of simplification such as minimum slab thicknesses. If the codes were to be adjusted to require greater thicknesses or use more conservative analysis, that may result in designs that are thicker than needed. Using thicker slabs means greater cost to the owner as well as larger impacts on the environment. In reality, it is up to society to accept the fact that this is a complicated matter, and not all slabs will end up being as flat as anticipated.

The interactions between those involved with engineering, architecture, construction, and ownership are complex and often riddled with pre-conceived notions about one another. Situations such as this flood event, where something went wrong and a responsible party may be needed, only complicates these ideas that the different trades have about each other. It would not be far-fetched for one party to blame the engineers for excessive deflection while citing the fact that the engineer came up with the design. In the same breath, the contractor may also be blamed if it is found that the design is acceptable. One may think that the only way an acceptable design is experiencing trouble is if the contractor did not build it properly. The contractor may blame the manufacturer who provided the materials, and the finger pointing can continue forever until a final ruling is reached in court. However, when it ultimately comes down to the fact that the code fell short and allowed for an excessive deflection situation, none of these trades are truly at fault. It serves as a reminder that a positive culture can be achieved if each trade respects one another and is not too quick to caste blame when things do not turn out as expected.

The environmental impacts of excessive slab deflections have to do mainly with the amount of concrete that is required to be poured. On one end, if it is desired to limit deflections, then a greater slab thickness may be needed. If that is the case, then the increase in concrete will result in a larger carbon footprint. For context, in the 13,000 sq. ft. basement, an increase of just 1 in. of slab thickness requires 40 cu. yd. of additional concrete to be poured. As buildings get larger and stories are added, that additional material increases quickly. This will also result in

slight increases in the building's seismic weight, which can cause other building members to increase in size. The other side of things is that if prestressing techniques are used, slabs can achieve greater strength with less thickness. However, that will make the slabs more deflection sensitive. If a prestressed slab does experience deflection issues after it has already been in service and must be replaced, the whole appeal of using a prestressed slab proves to be counter-productive. Now, the environmental impacts of two slabs are endured rather simply pouring the first slab at a greater thickness. Ultimately, the carbon footprint of the slab is proportional to the amount of concrete that it uses over its lifespan, including replacing the slab if that is required.

Similar to the environmental impacts, one of the driving factors for economic impact of this project revolves around the use of material. Designs that use more concrete will ultimately end up costing more. Not only will the cost of materials increase if a slab needs to be poured to a greater depth, but the amount of labor will also increase. Pouring more concrete means more hours of mixing and preparing the material, more trucks needed to transport material, and more hours spent actually pouring the slab. That being said, it is not only a worthy investment environmentally to get it right the first time. Slabs that are not poured to a proper depth and need to be replaced during their usable lifetime will ultimately cost the most. Demolition of the previous slab and all of the materials and labor being needed for a repair or replacement will of course prove to be the costliest. It is economically advantageous to design a slab that will never have to be replaced while at the same time having a depth that does not go far beyond what is needed for its service.

Lifelong Learning

When looking at a calculation that is seemingly unfeasible, it is important to take a step back and break things down into parts. The ACI initially only predicted 30% of the actual deflection. Many engineers may stop there any say something else went wrong, and possibly even say the slab is faulty and needs to be replaced. However, upon further investigation, many things may come to light that make the whole picture make sense. After researching and seeing that slab deflections have plagued many engineers over time, it was very helpful to see how different authors accounted for that fact and adjust certain factors. Then, by not blindly trusting the fact that the slab was poured to the correct thickness, the slab deflections became a

lot more reasonable. It was just a matter of gaining insight into what was really happening.

Another key learning point from this project is to not blindly trust the code. It is important as an engineer to have doubt about things and question their validity. In this case, ACI 318-19 was not a great guide to properly predicting deflections. A good rule of thumb is to use the code as a minimum, but it is always permissible and sometimes even necessary to take things a step further than the code requires in order to produce quality calculations.

Bibliography

[1] https://www.enggcyclopedia.com

[2] https://www.ardexbuildingproducts.ie

[3] https://ascelibrary.org

[4] https://conquertermites.com

[5] https://youtube.com/StructurePoint

[6] https://www.StructurePoint.org

[7] ACI 318-19

Appendix A – Deflection Calculation

$$\Delta_{IMM} = \frac{(\Delta_{cy}+\Delta_{mx})+(\Delta_{my}+\Delta_{cx})}{2} = \frac{(0.47"+0.03")+(0.25"+0.10")}{2} = \underline{0.42''} \text{ (Including Flood)}$$

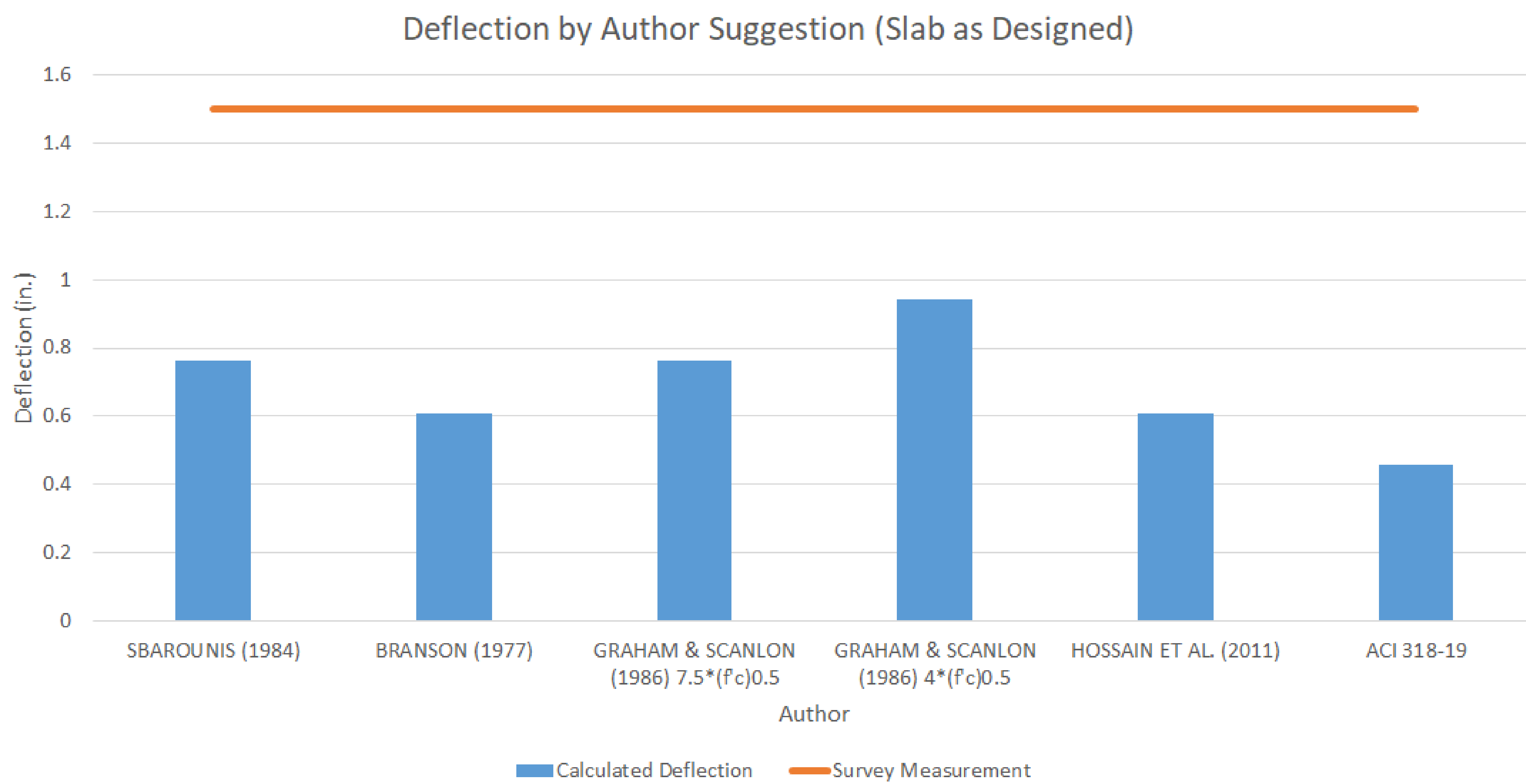
$$\Delta_{IMM} = \Delta_{IMM} * \frac{1}{2}\left(\frac{M_{STTOTX(D+SUSL)}}{M_{STTOTX(MAX)}} + \frac{M_{STTOTY(D+SUSL)}}{M_{STTOTY(MAX)}}\right)$$

$$= 0.42'' * \frac{1}{2}\left(\frac{433\ K*IN}{1098\ K*IN} + \frac{515\ K*IN}{1589\ K*IN}\right) = \underline{0.15''} \text{ (Sustained After Flood)}$$

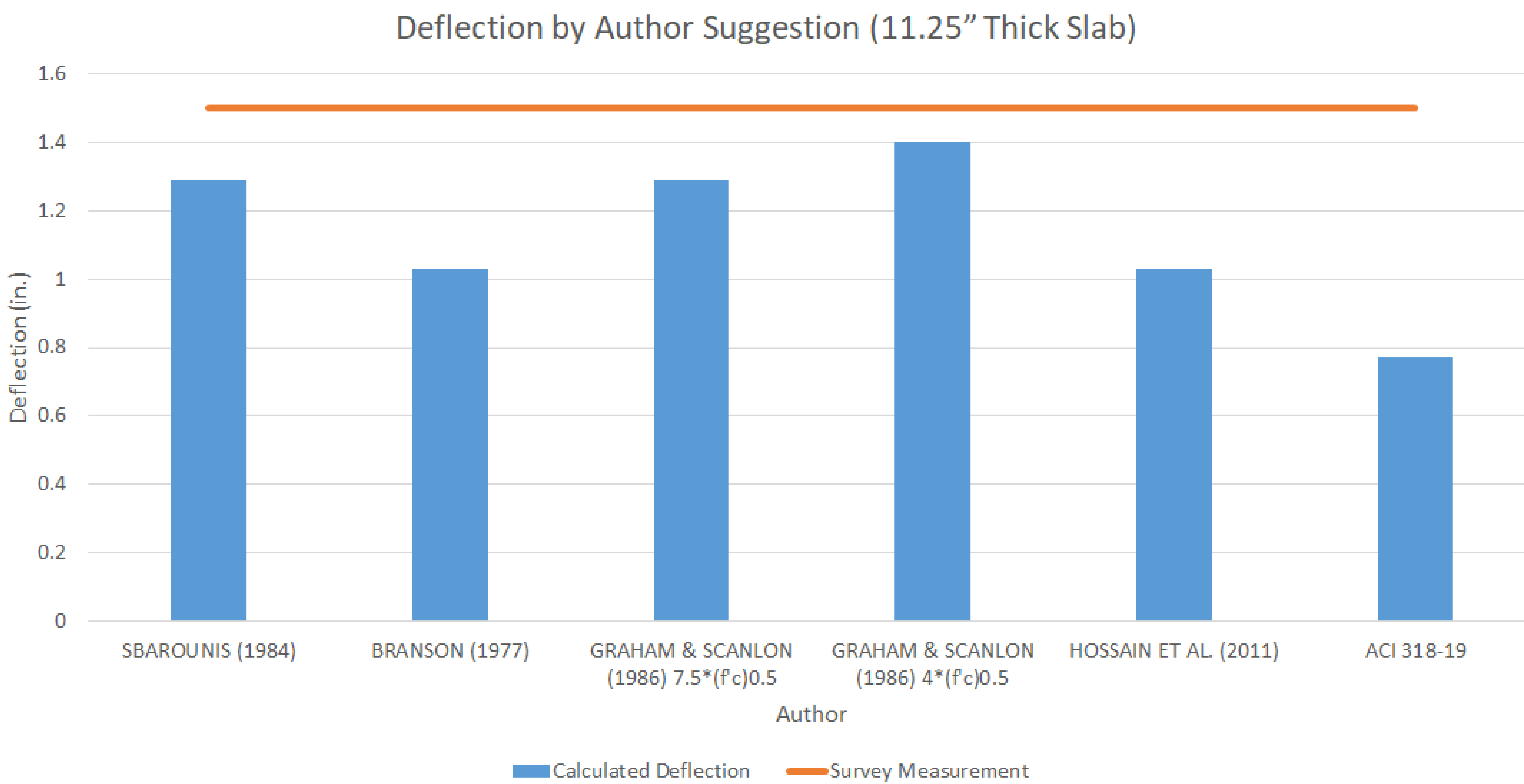
$$\Delta_{LONGTERM} = \Delta_{IMM} * \lambda_{\Delta} = 0.15'' * (2+1) = \boxed{0.45''} \text{ (Long Term Deflection)}$$

Appendix B – Deflections per Author Recommendation

13 INCH THICK SLAB																
						FULL LOADING INCLUDING FLOOD							DEAD + SUSTAINED LIVE			
SOURCE	MODULUS OF RUPTURE	IMMEDIATE	CREEP λ_C	SHRINKAGE λ_{SH}	TOTAL λ_T	Δ_{CX}	Δ_{MX}	Δ_{CY}	Δ_{MY}	$\Delta_{TOTIMMEDIATE}$	M_{STTOTX}	M_{STTOTY}	M_{STTOTX}	M_{STTOTY}	$\Delta_{TOTIMMEDIATE}$	$\Delta_{TOTLONGTERM}$
SBAROUNIS (1984)	$7.5*(f'_c)^{0.5}$	1	2.8	1.2	5	0.098	0.03	0.473	0.246	0.4235	1098	1589	433	515	0.15213318	0.760665903
BRANSON (1977)	$7.5*(f'_c)^{0.5}$	1	2	1	4	0.098	0.03	0.473	0.246	0.4235	1098	1589	433	515	0.15213318	0.608532723
GRAHAM & SCANLON (1986)	$7.5*(f'_c)^{0.5}$	1	2	2	5	0.098	0.03	0.473	0.246	0.4235	1098	1589	433	515	0.15213318	0.760665903
	$4*(f'_c)^{0.5}$	1	1.5	1	3.5	0.172	0.057	0.843	0.429	0.7505	1098	1589	433	515	0.26960083	0.94360291
HOSSAIN ET AL. (2011)	$7.5*(f'_c)^{0.5}$	1	3		4	0.098	0.03	0.473	0.246	0.4235	1098	1589	433	515	0.15213318	0.608532723
ACI 318	$7.5*(f'_c)^{0.5}$	1	2		3	0.098	0.03	0.473	0.246	0.4235	1098	1589	433	515	0.15213318	0.456399542



11.25 INCH THICK SLAB																
						FULL LOADING INCLUDING FLOOD							DEAD + SUSTAINED LIVE			
SOURCE	MODULUS OF RUPTURE	IMMEDIATE	CREEP λ_C	SHRINKAGE λ_{SH}	TOTAL λ_T	Δ_{CX}	Δ_{MX}	Δ_{CY}	Δ_{MY}	$\Delta_{TOTIMMEDIATE}$	M_{STTOTX}	M_{STTOTY}	M_{STTOTX}	M_{STTOTY}	$\Delta_{TOTIMMEDIATE}$	$\Delta_{TOTLONGTERM}$
SBAROUNIS (1984)	$7.5*(f'_c)^{0.5}$	1	2.8	1.2	5	0.149	0.046	0.908	0.465	0.784	1060	1580	388	459	0.25736527	1.286826367
BRANSON (1977)	$7.5*(f'_c)^{0.5}$	1	2	1	4	0.149	0.046	0.908	0.465	0.784	1060	1580	388	459	0.25736527	1.029461094
GRAHAM & SCANLON (1986)	$7.5*(f'_c)^{0.5}$	1	2	2	5	0.149	0.046	0.908	0.465	0.784	1060	1580	388	459	0.25736527	1.286826367
	$4*(f'_c)^{0.5}$	1	1.5	1	3.5	0.367	0.126	1.291	0.658	1.221	1060	1580	388	459	0.40082015	1.402870531
HOSSAIN ET AL. (2011)	$7.5*(f'_c)^{0.5}$	1	3		4	0.149	0.046	0.908	0.465	0.784	1060	1580	388	459	0.25736527	1.029461094
ACI 318	$7.5*(f'_c)^{0.5}$	1	2		3	0.149	0.046	0.908	0.465	0.784	1060	1580	388	459	0.25736527	0.77209582



Appendix C – PowerPoint Slides

Two-Way Slab Deflections

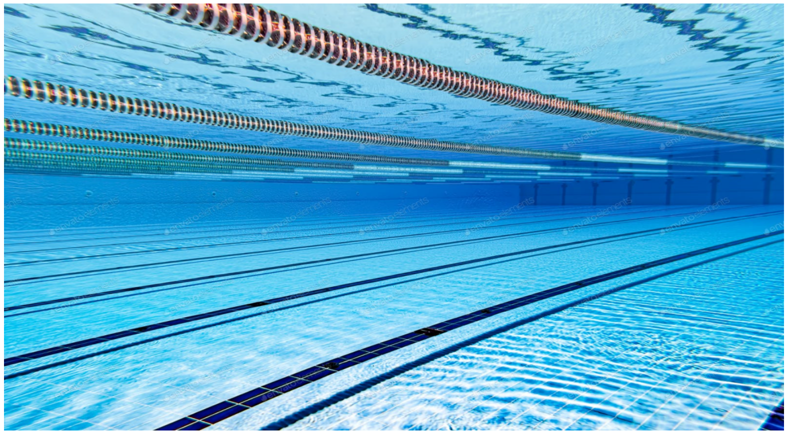
By: Matthew Frydman, EIT
Advisor: John Lawson, PE, SE, Professor

Wiss Janey Elstner Associates, Inc.

- Architects, Engineers, Materials Scientists
- Summer internship
  - Denver, Colorado
  - Structural investigations/repair design
  - Natural Elements
    - Fire, water, corrosion, etc.

Case Study

- Project manager receives a call about a large flood
  - Built in the late 1990's
  - Two stories
  - 13,000 square foot basement
  - 8-10 foot flood reported
    - 1.25 Olympic swimming pools worth of water!



SOURCE: https://istockphoto.com

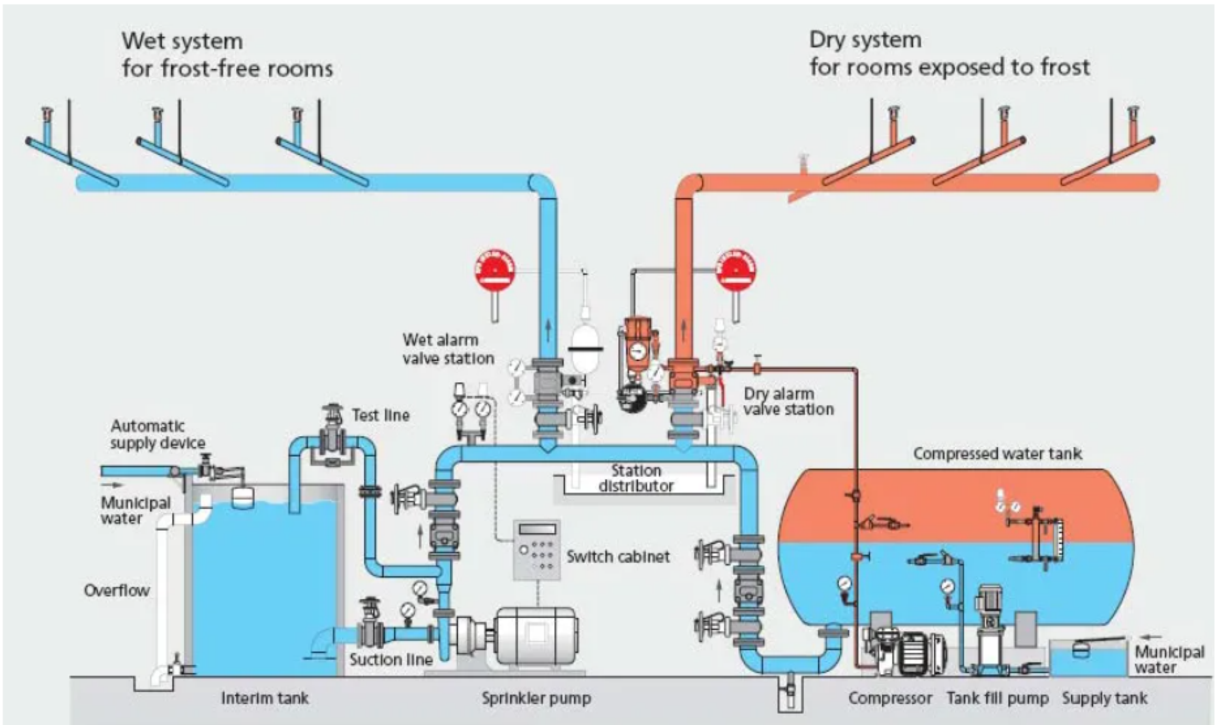
Flood Event

- Water based fire suppression line
  - Froze, expanded, and burst
  - Went unnoticed for hours
  - Water pumped out over a subsequent week

SOURCE: https://imgur.com

Avoiding the Problem

- A dry pipe sprinkler could have avoided the flood event altogether



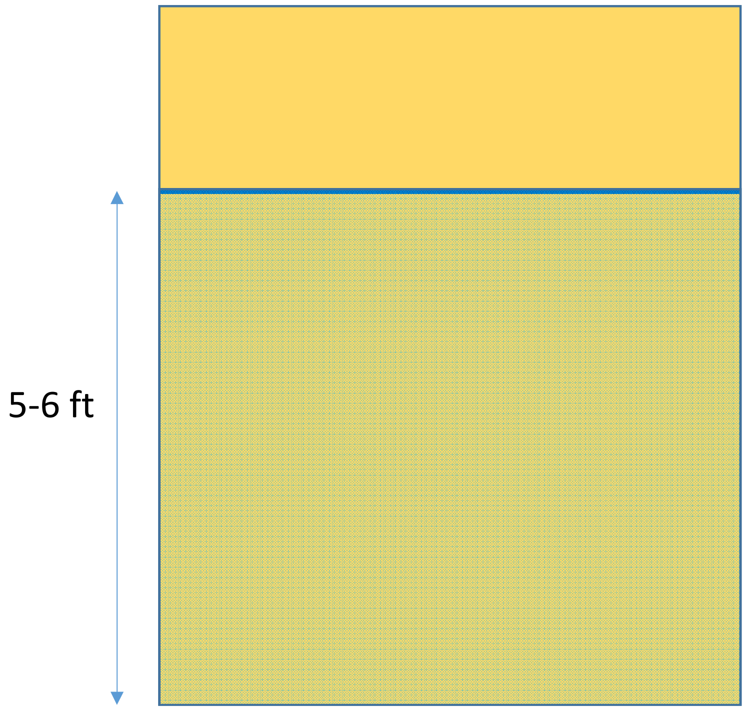
SOURCE: https://www.enggcyclopedia.com

Our Objectives

- Determine if the flood event:
  - Caused structural damage
  - Impacted the slab’s serviceability capability (deflection)

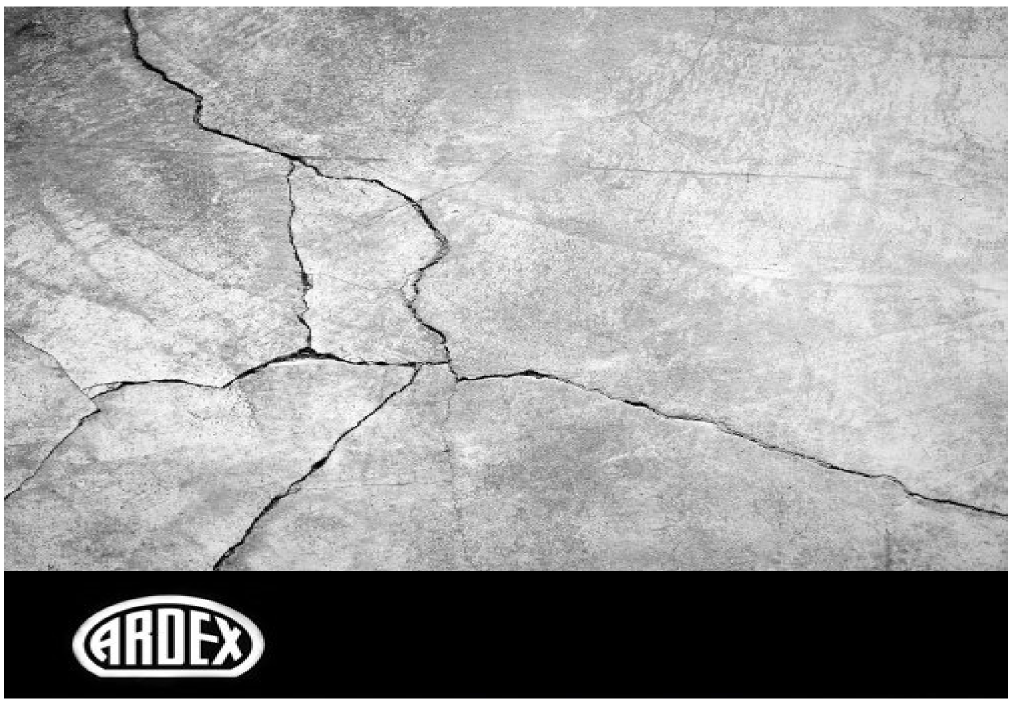
Site Visit

- Non-destructive visual observation
  - Water stain line on sheathing in elevator shaft
    - Closer to 5 or 6 feet of flooding (compared to 8-10 feet reported)



Site Visit

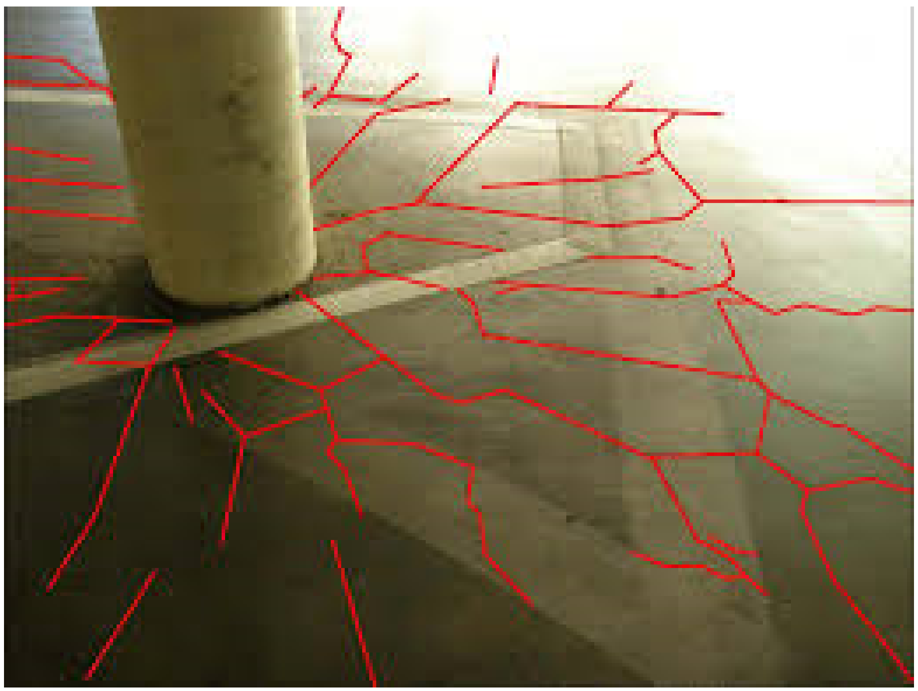
- Non-destructive visual observation
  - Clean, sharp cracking in areas of top-surface tension
    - Crack widths reached 1/16”



SOURCE: https://www.ardexbuildingproducts.ie

Site Visit

- Non-destructive visual observation
  - Concentrated cracking around interior columns aligned with foundation support piers



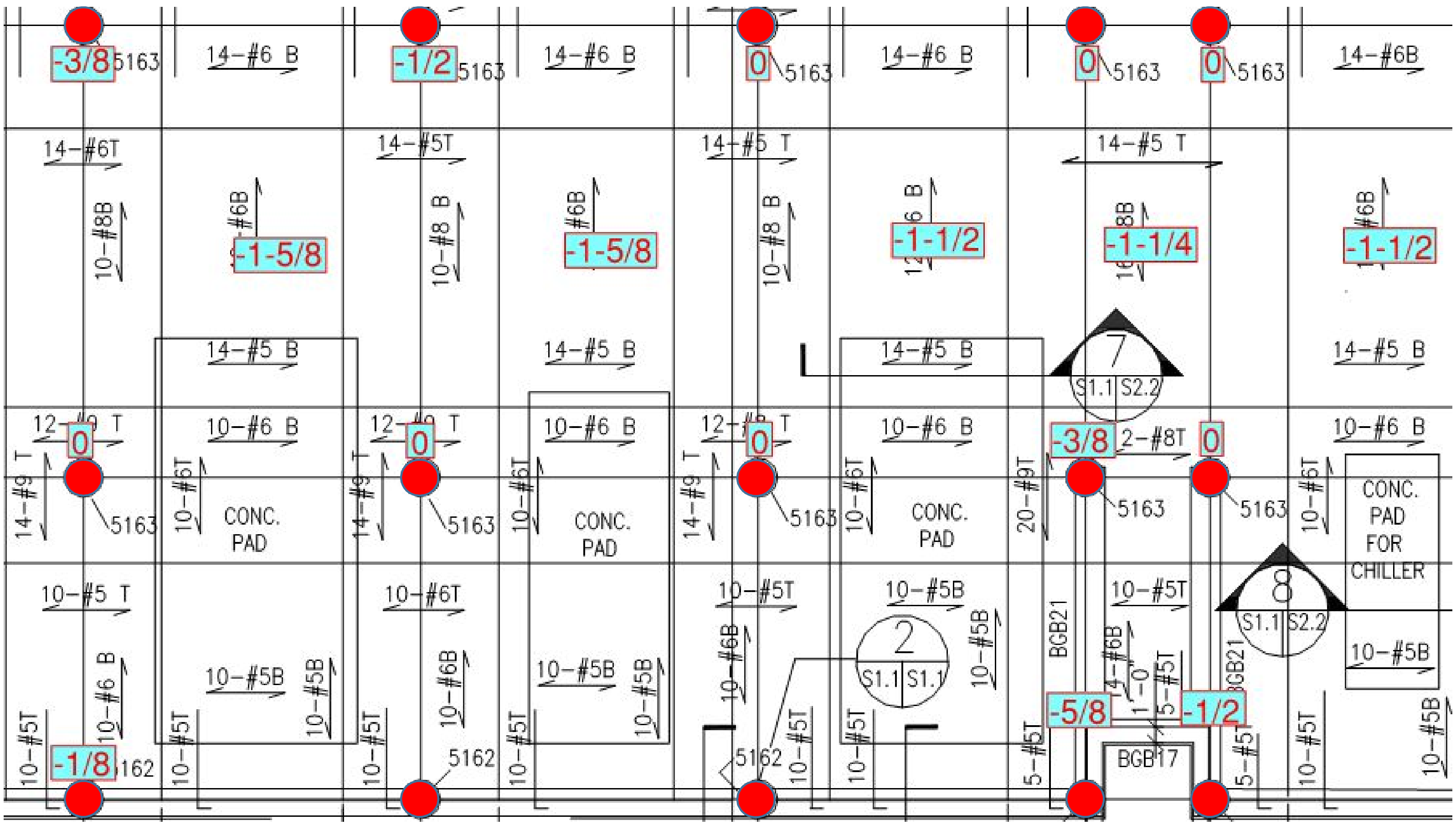
SOURCE: https://ascelibrary.org

Site Visit

- Non-destructive visual observation
  - Slab cutout made to facilitate plumbing repairs
    - Slab thickness ranged from 10.5” – 12.25”
      - Less than the specified 13”

SOURCE: https://conquertermites.com.

Relative Elevation survey

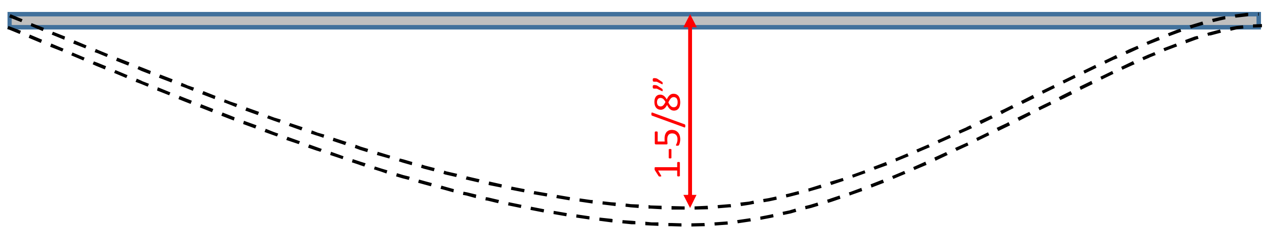


Site Visit Takeaways/Concerns

- Punching shear
  - Cracking around columns indicates potential initiation of punching shear
  - Outside the scope of this project
- Excessive Slab Deflection
  - 1-5/8" deflection at midspan in both directions may be considered excessive
    - $\frac{L}{214}$
  - Newly formed cracks may reduce slab stiffness
    - Increased deflection under service loads moving forward
- Slab Strength
  - Load testing philosophy

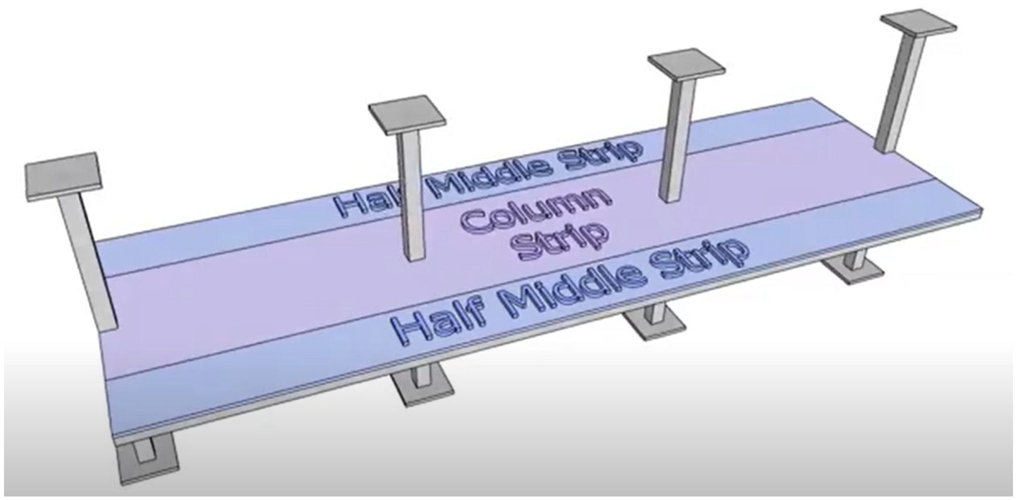
1-5/8” Slab Deflection

- Is this permanent deflection due to the flood event?
  - Are there any other viable explanations?
- Is this a cause for concern?



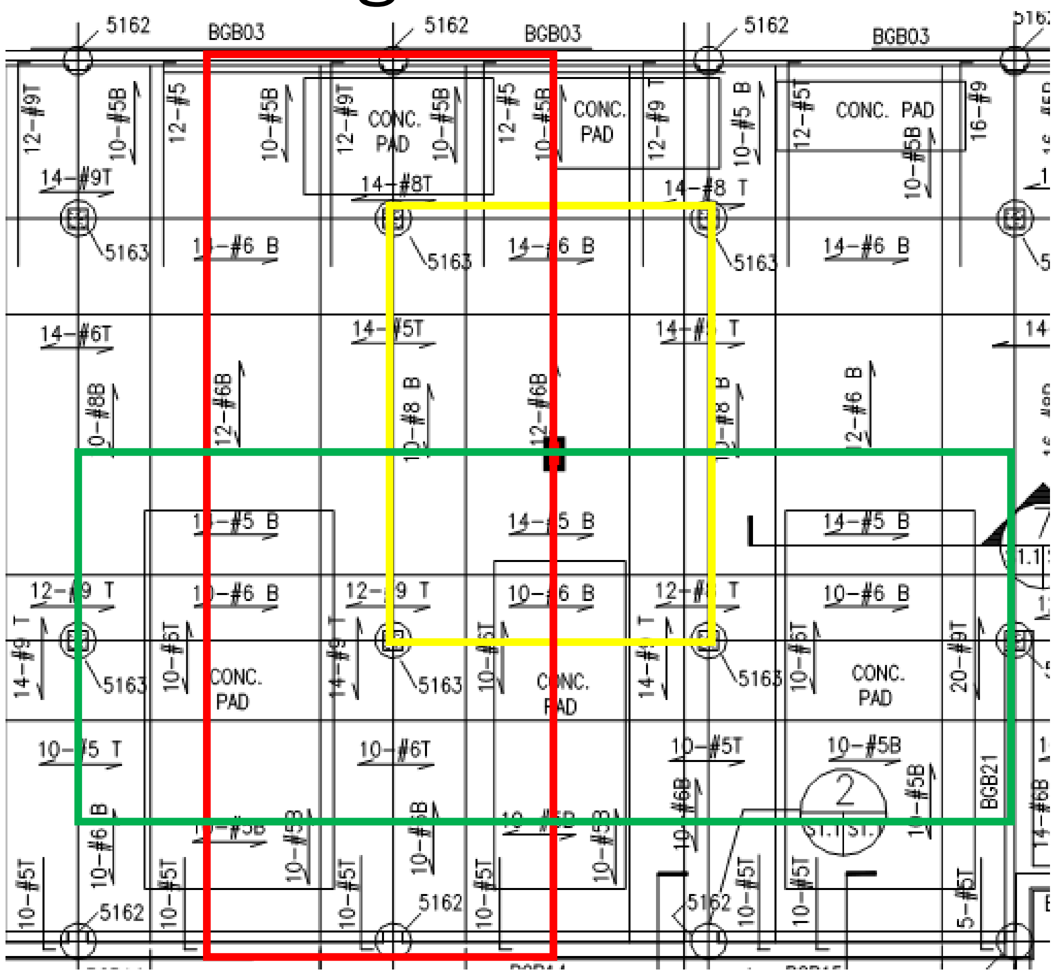
Equivalent Frame Method (EFM)

- Models a 3-D structure as a series of 2-D frames centered along support lines

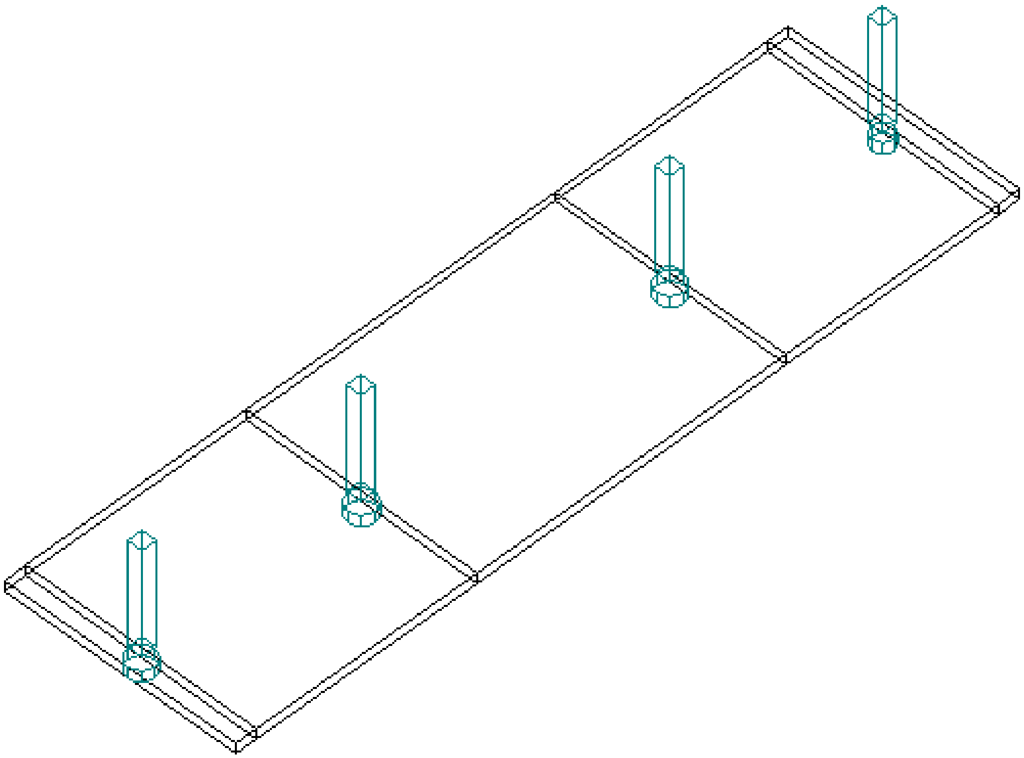


SOURCE: https://youtube.com/StructurePoint

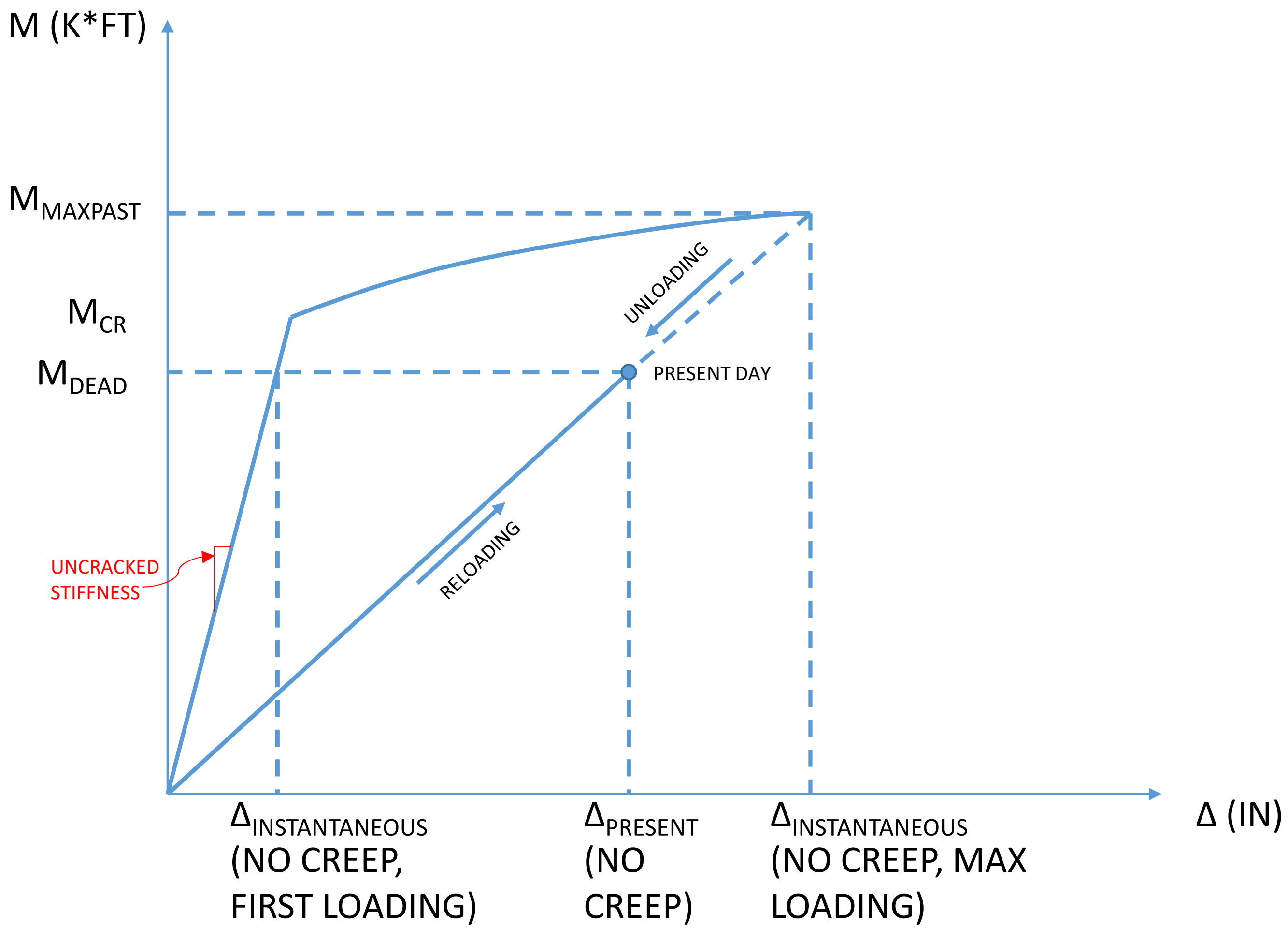
spSlab Modeling



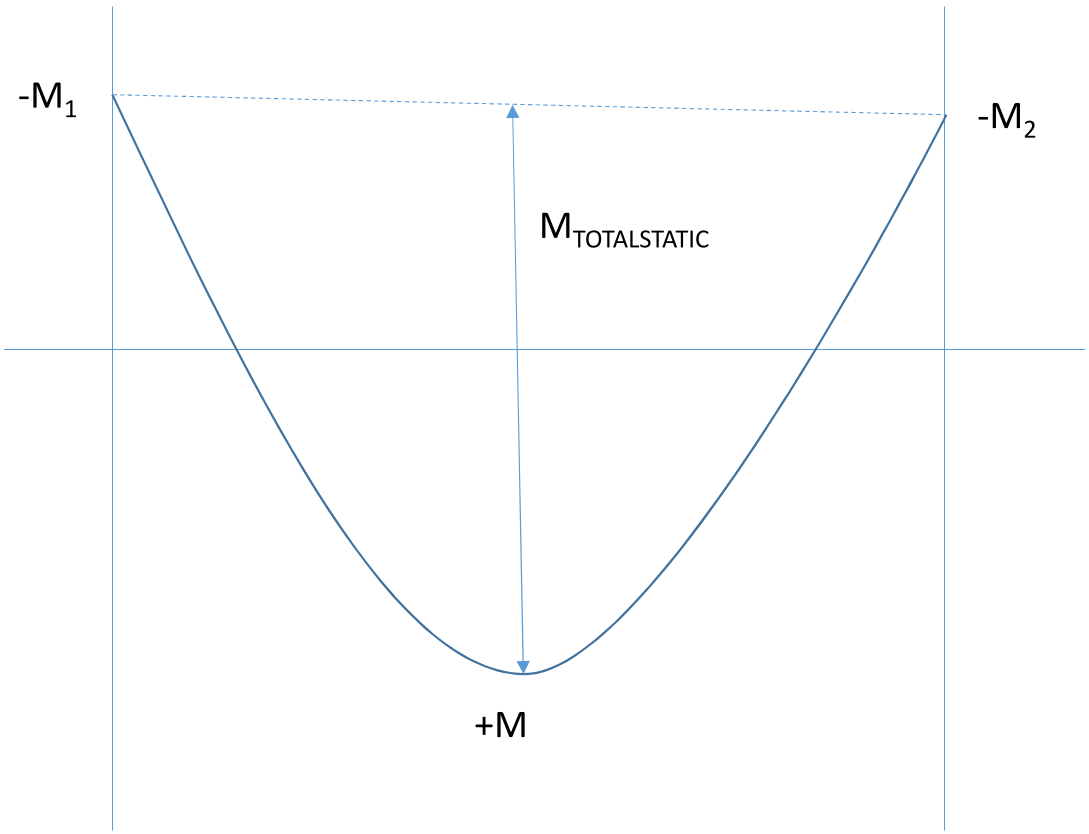
spSlab Modeling



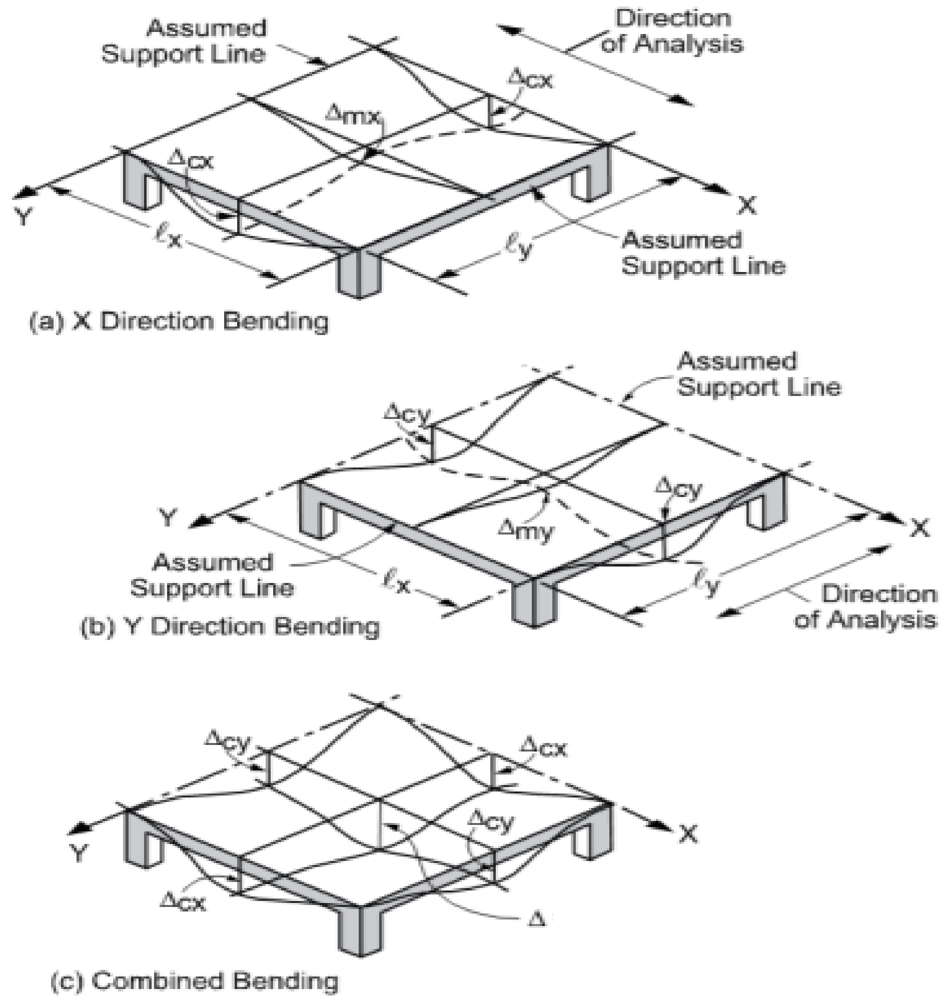
DEFLECTION VS. TOTAL STATIC MOMENT



Total Static Moment



$$\Delta = \frac{\left(\Delta_{cy} + \Delta_{mx}\right) + \left(\Delta_{my} + \Delta_{cx}\right)}{2}$$



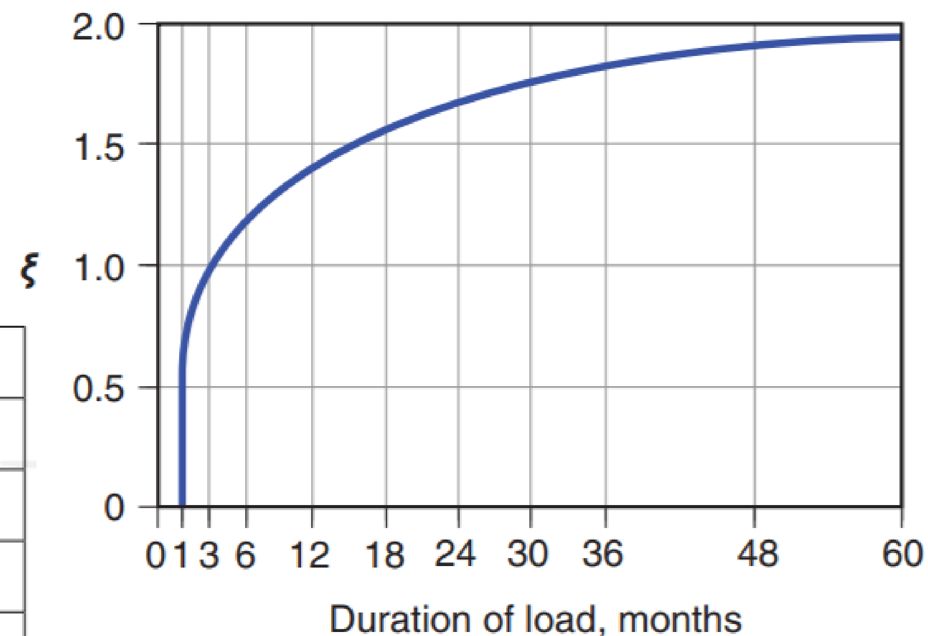
SOURCE: https://www.StructurePoint.org

Additional Time-Dependent Deflection (λ_Δ)

- Due to creep and shrinkage
- ACI 318-19

$$\lambda_\Delta = \frac{\xi}{1+50\rho'}$$

Sustained load duration, months	Time-dependent factor ξ
3	1.0
6	1.2
12	1.4
60 or more	2.0



Initial ACI Deflection Prediction

$\Delta_{IMM} = \frac{(\Delta_{cy}+\Delta_{mx})+(\Delta_{my}+\Delta_{cx})}{2} = \frac{(0.47"+0.03")+(0.25"+0.10")}{2} = \underline{0.42"}$ (Including Flood)

$\Delta_{IMM} = \Delta_{IMM} * \frac{1}{2}\left(\frac{M_{STTOTX(D+SUSL)}}{M_{STTOTX(MAX)}} + \frac{M_{STTOTY(D+SUSL)}}{M_{STTOTY(MAX)}}\right)$

$= 0.42" * \frac{1}{2}\left(\frac{433\ K*IN}{1098\ K*IN} + \frac{515\ K*IN}{1589\ K*IN}\right) = \underline{0.15"}$ (Sustained After Flood)

$\Delta_{LONGTERM} = \Delta_{IMM} * \lambda_{\Delta} = 0.15" * (2+1) = \boxed{0.45"}$ (Long Term Deflection)

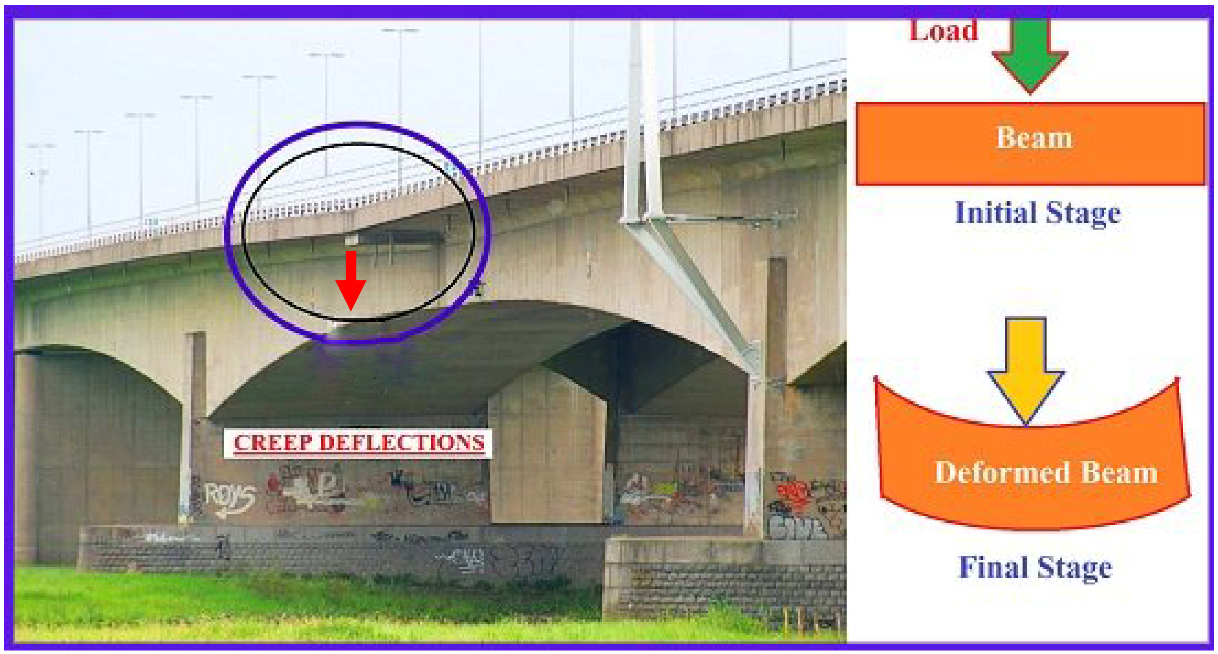
30% OF MEASURED DEFLECTION!!

Parametric Study

- Creep Factor (λ_c)
- Shrinkage Factor (λ_{sh})
- Modulus of Rupture (f_r)

Deflection Due to Creep (λ_c)

- Deflection under sustained loads over time
- Main factor is mix proportions
  - Water/cement ratio



SOURCE: https://www.civilconcept.com

Deflection Due to Shrinkage (λ_{sh})

- Volume change due to moisture loss causes shrinkage cracks
- Rebar restraint may increase cracking

SOURCE: https://www.aboutcivil.org

Modulus of Rupture (f_r)

- Tensile strength of concrete in flexure
- ACI 318-19
  - $f_r = 7.5\lambda\sqrt{f'_c}$
    - $\lambda = 1.0$ (normal weight concrete)

Effective Moment of Inertia (I_{eff})

$$M_{cr} = \frac{f_r I_g}{y_t}$$

Service moment	Effective moment of inertia, I_e, in.^{4}	
$M_a \le (2/3)M_{cr}$	I_g	(a)
$M_a > (2/3)M_{cr}$	$\dfrac{I_{cr}}{1-\left(\dfrac{(2/3)M_{cr}}{M_a}\right)^2\left(1-\dfrac{I_{cr}}{I_g}\right)}$	(b)

ACI 318-19 24.2.3.5

Recommendations by Author

<table>
<tr><th>SOURCE</th><th>MODULUS OF RUPTURE</th><th>IMMEDIATE</th><th>CREEP λ_C</th><th>SHRINKAGE λ_{SH}</th><th>TOTAL λ_T</th></tr>
<tr><td>SBAROUNIS (1984)</td><td>$7.5*(f'_c)^{0.5}$</td><td>1</td><td>2.8</td><td>1.2</td><td>5</td></tr>
<tr><td>BRANSON (1977)</td><td>$7.5*(f'_c)^{0.5}$</td><td>1</td><td>2</td><td>1</td><td>4</td></tr>
<tr><td rowspan="2">GRAHAM & SCANLON (1986)</td><td>$7.5*(f'_c)^{0.5}$</td><td>1</td><td>2</td><td>2</td><td>5</td></tr>
<tr><td>$4*(f'_c)^{0.5}$</td><td>1</td><td>1.5</td><td>1</td><td>3.5</td></tr>
<tr><td>HOSSAIN ET AL. (2011)</td><td>$7.5*(f'_c)^{0.5}$</td><td>1</td><td colspan="2">3</td><td>4</td></tr>
<tr><td>ACI 318</td><td>$7.5*(f'_c)^{0.5}$</td><td>1</td><td colspan="2">2</td><td>3</td></tr>
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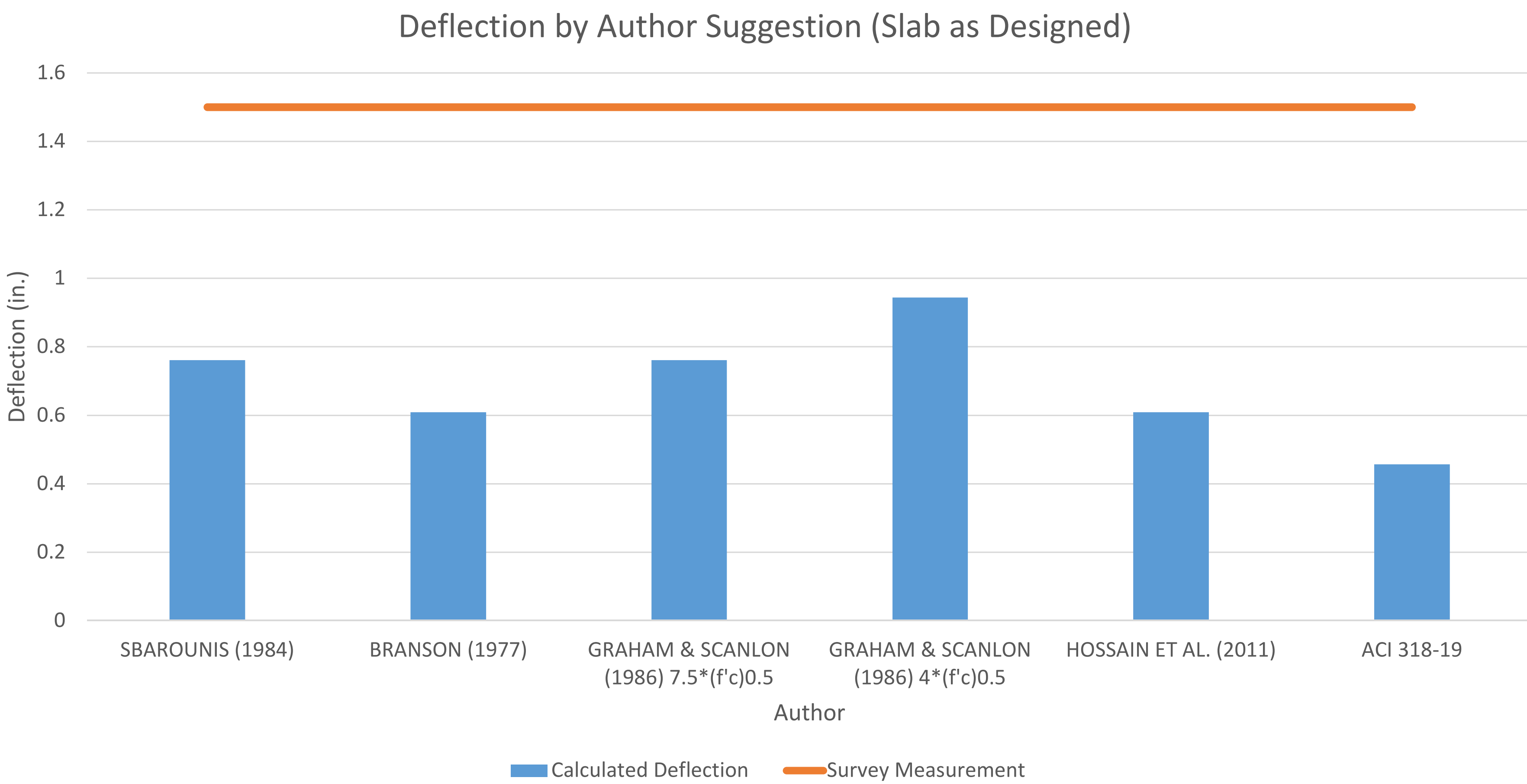
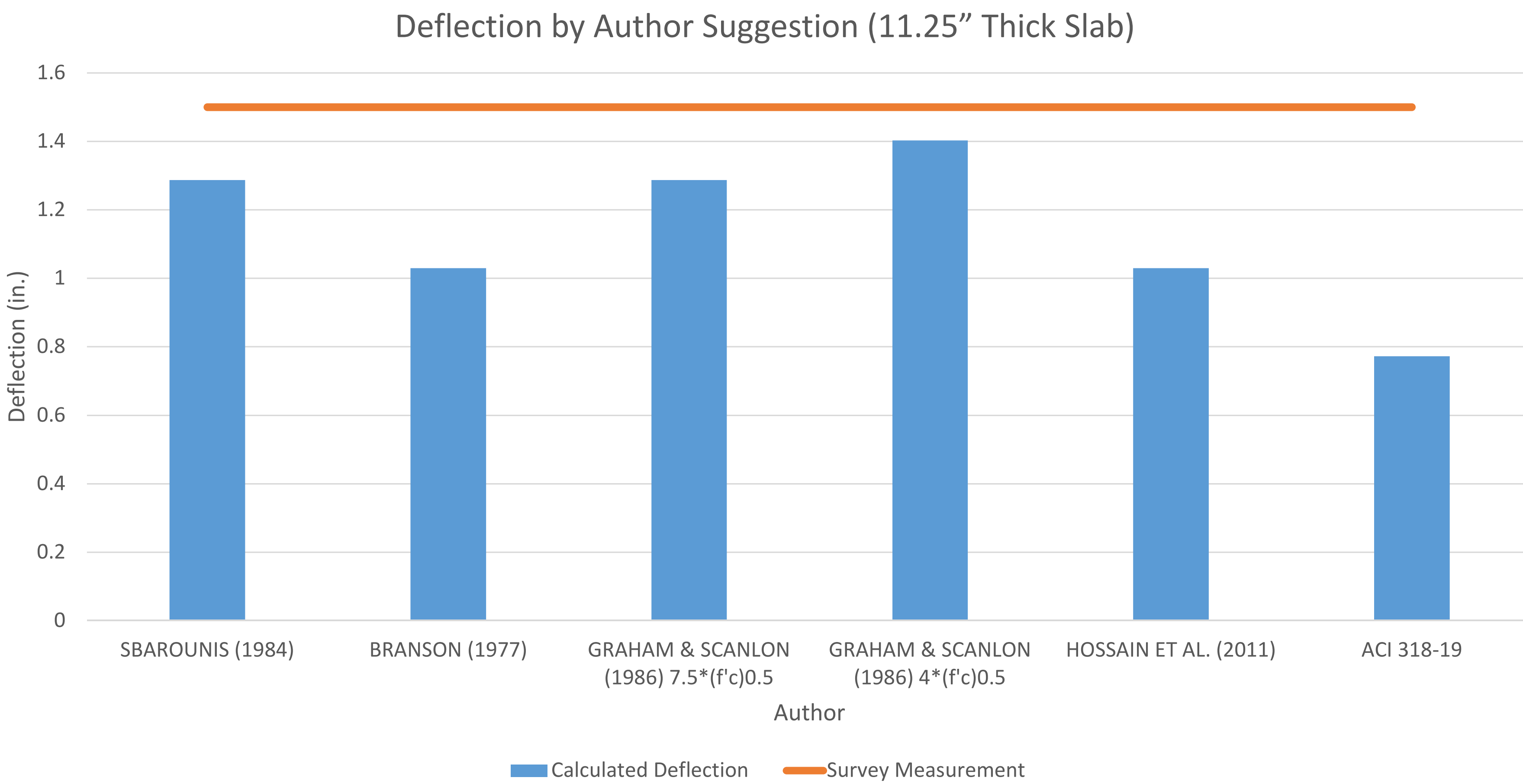


GRAHAM AND SCANLON: 0.94” (62% OF MEASURED DEFLECTION)

Is There Another Possibility?

- Previous deflections were based on a 13” thick slab
- An extremely small field sample showed a slab thickness range between 10.5” and 12.25”
  - What is the deflection if the slab was 11.25”? (Average)



GRAHAM AND SCANLON: 1.41” (93% OF MEASURED DEFLECTION)

What About Strength?

- Load testing philosophy
  - ACI 318-19 Chapter 27

27.4.2 Load tests shall be conducted in a manner that provides for safety of life and the structure during the test.

27.4.6.1 Test load arrangements shall be selected to maximize the load effects in the critical regions of the members being evaluated.

(a) $T_t = 1.0D_w + 1.1D_s + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$ (27.4.6.2a)

(b) $T_t = 1.0D_w + 1.1D_s + 1.0L + 1.6(L_r \text{ or } S \text{ or } R)$ (27.4.6.2b)

(c) $T_t = 1.3(D_w + D_s)$ (27.4.6.2c)

At 6ft of water:

T_t = 62.4pcf * 6ft = 374 psf

What About Strength?

- Load testing philosophy
  - ACI 318-19 Chapter 27

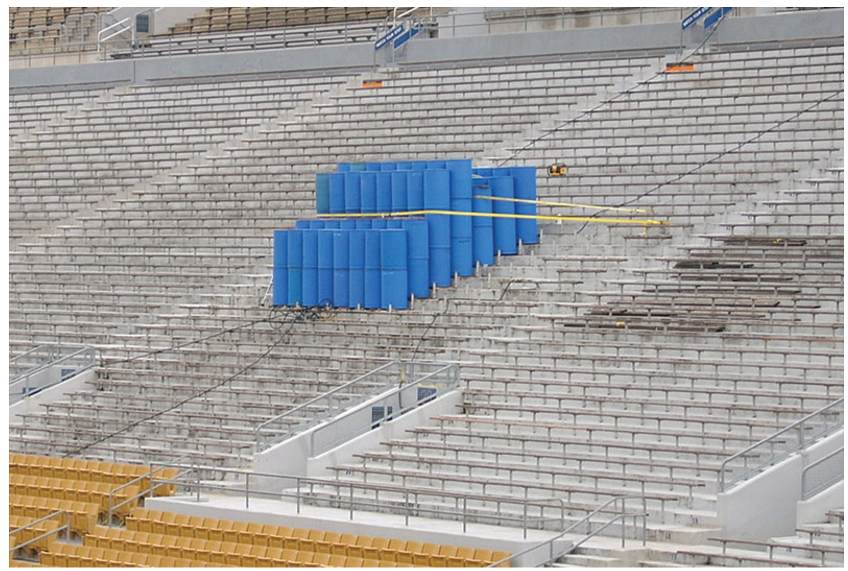
27.5.2.1 Response measurements, such as deflection, strain, slip, and crack width, shall be made at locations where maximum response is expected. Additional measurements shall be made if required.

27.5.3.1 The portion of the structure tested shall show no spalling or crushing of concrete, or other evidence of failure.

27.5.3.2 Members tested shall not exhibit cracks indicating imminent shear failure.

What About Strength?

- Load testing philosophy
  - If a structure can handle a large enough load, it can be deemed code compliant despite design flaws or loading history



SOURCE: https://www.structuremag.org

Conclusions

- The excessive deflection may have an explanation
  - Destructive field observations would confirm/deny
- Codified methods are often unconservative in predicting deflections
- Risk of strength loss is not a large concern

QUESTIONS?