American Concrete Institute®
Advancing concrete knowledge

Recent Development in Reinforced Concrete Slab Analysis, Design, and Serviceability

ACI Fall 2011 Convention
October 16 – 20, Cincinnati, OH

ACI WEB SESSIONS

ACI Web Sessions

The audio for this web session will begin momentarily and will play in its entirety along with the slides.

However, if you wish to skip to the next speaker, use the scroll bar at left to locate the speaker's first slide (indicated by the icon in the bottom right corner of slides 10 and 38). Click on the thumbnail for the slide to begin the audio for that portion of the presentation.

Note: If the slides begin to lag behind the audio, back up one slide to re-sync.

ACI WEB SESSIONS

ACI Web Sessions

ACI is bringing you this Web Session in keeping with its motto of "Advancing Concrete Knowledge." The ideas expressed, however, are those of the speakers and do not necessarily reflect the views of ACI or its committees.

Please adjust your audio to an appropriate level at this time.

ACI WEB SESSIONS

ACI Web Sessions

ACI Web Sessions are recorded at ACI conventions and other concrete industry events. At regular intervals, a new set of presentations can be viewed on ACI's website free of charge.

After one week, the presentations will be temporarily archived on the ACI website or made part of ACI's Online CEU Program, depending on their content.

ACI WEB SESSIONS

ACI Online CEU Program

ACI offers an easy-to-use Online CEU Program for anyone who needs to earn Continuing Education credits.

Once registered, you can download and study reference material. After passing a 10-question exam on the material, you will receive a certificate of completion that you can present to local licensing agencies.

Visit **www.concrete.org/education/edu_online_CEU.htm** for more information.

ACI WEB SESSIONS

ACI Conventions

ACI conventions provide a forum for networking, learning the latest in concrete technology and practices, renewing old friendships, and making new ones. At each of ACI's two annual conventions, technical and educational committees meet to develop the standards, reports, and other documents necessary to keep abreast of the ever-changing world of concrete technology.

With over 1,300 delegates attending each convention, there is ample opportunity to meet and talk individually with some of the most prominent persons in the field of concrete technology. For more information about ACI conventions, visit www.aciconvention.org.

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ACI Web Sessions

This ACI Web Session includes 2 speakers presenting at the ACI fall convention held in Cincinnati, OH, October 16 – 20, 2011.

Additional presentations will be made available in future ACI Web Sessions.

Please enjoy the presentations.

ACI WEB SESSIONS

Fall 2011 Seminars

These seminars, cosponsored by ACI and the Portland Cement Association (PCA), will cover all the major changes in the new edition of the **318-11 Building Code**.

DATE	LOCATION
November 15	Des Moines, IA
November 17	Portland, OR
November 29	Denver, CO
December 1	Phoenix, AZ
December 6	Atlanta, GA
December 8	Washington, DC
December 13	Dallas, TX
December 15	San Francisco, CA

For more information, visit ACI Seminars.

ACI WEB SESSIONS

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Recent Development in Reinforced Concrete Slab Analysis, Design, and Serviceability

ACI Fall 2011 Convention
October 16 – 20, Cincinnati, OH

ACI WEB SESSIONS

Eva Lantsoght, Ph.D. candidate, Delft University of Technology, Netherlands. Her Ph.D. topic is Reinforced Concrete Slabs Under Concentrated Loads Close to Support.

ACI WEB SESSIONS

Shear Capacity of Slabs and Slab Strips
Loaded Close to the Support

Eva Lantsoght
8-11-2011

ACI WEB SESSIONS

Overview

- Introduction
- Experiments
- Results
  - Shear span to depth ratio
  - Size of loading plate
  - Overall width/Effective width
  - Comparison to Code methods
- Conclusions

S9T6 at failure

Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

ACI WEB SESSIONS

Introduction
Project description (1)

- Capacity of existing bridges in NL
  - TU Delft
    - Concrete Structures
    - Structural Mechanics
  - TNO
  - RWS
- 3715 relevant structures
- 2020 built before 1976
- Study: bridge categories and specific details

Highways in the Netherlands

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

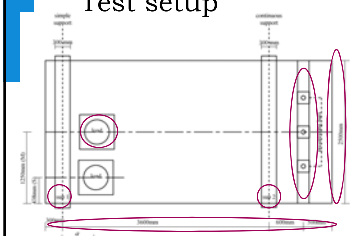
Introduction
Project description (2)

- Concrete Structures
  - Long-term tensile strength
  - Beam shear – sustained loads
  - Continuous girders – shear
  - Prestressed slabs – punching + CMA
  - **Slab bridges - shear / punching**

Concrete bridges

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Experiments
Test setup



Size: 5m x 2,5m x 0,3m

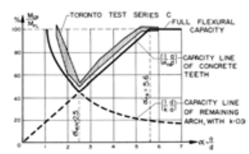
Continuous support, Line supports

Load: vary a/d and position along width

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Shear span to depth ratio
Introduction (1)

- Important parameter in tests
- Influence on M_{cr}/M_{fl}
- Small *a/d*
  - Direct load transfer
  - Compression strut

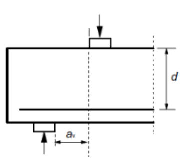


Valley of shear failure (Kani 1964)

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Shear span to depth ratio
Introduction (2)

- Eurocode:
  - Direct load transfer
  - $0.5d \leq a_v \leq 2d$
  - $\beta = a_v/2d$
- Reduces contribution of load to shear force

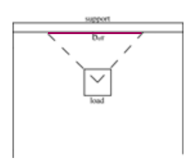


EN 1992-1-1:2005 Figure 6.4

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Shear span to depth ratio
Introduction (3)

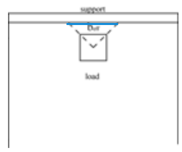
- Slabs: Effective width
  - Assume uniform stress
  - Maximum stress over effective width
- Load spreading 45° for design



ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

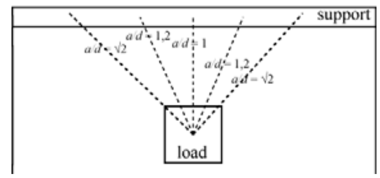
Shear span to depth ratio Introduction (4)

- Lower bound: $2d$
- Loads closer to support:
  - Smaller b_{eff}
  - Smaller V_{ult}
- In beams: direct load transfer
  - Larger V_{ult}



ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Shear span to depth ratio Introduction (3)



- Direct load transfer + Smaller effective width
- Three-dimensional behavior
- Larger effective a/d distance
- Lower increase P_u expected than for beams

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Shear span to depth ratio Results

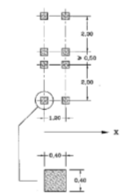
- Expected increase based on β (EC2):
  - Slabs: double
  - Strips: 80%
  - Different loading plate size
- Transition from beam (2D) to slab (3D)
- Different behavior in slabs

Specimens	b (m)	Average increase
BS2 – BS3	0.5	98%
BM2 – BM3	1.0	64%
BL2 – BL3	1.5	41%
BX2 – BX3	2.0	23%
S3/S4 – S5/S6	2.5	26%

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Size of loading plate Introduction (1)

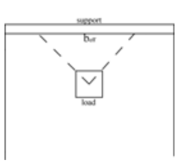
AASHTO loading truck
Tire contact area: 510mm x 250mm



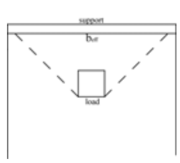
EN 1991-2 load model 1
400mm x 400mm

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Size of loading plate Introduction (2)



45° load spreading



45° load spreading – French practice

Influence size of loading plate on shear capacity?

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Size of loading plate Previous research

- Furuuchi et al (1998), Regan (1982)
  - Increase in rectangularity
  - Increase in ultimate load
- Sherwood et al (2006), Serna-Ros et al (2002)
  - Load and support points narrower than specimen width
  - Small detrimental effect on shear capacity
- Increase in size for square loading plate?

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Size of loading plate
Test results (1)

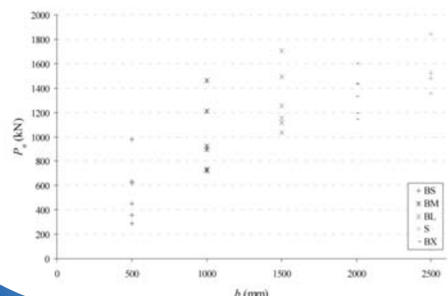
Specimens	*b* (m)	Average increase
BS1 – BS3	0.5	10.1%
BM1 – BM3	1.0	0.5%
BL1 – BL3	1.5	0.7%
BX1 – BX3	2.0	25.2%
S1 – S2	2.5	41.5%

- Comparison 200mm x 200mm / 300mm x 300mm
- Increasing influence for larger width
- Large loading plate: larger surface to start 3D struts

Overall width and Effective width
Previous research

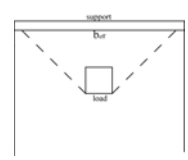
- Concept of effective width?
  - Regan & Rezai-Jorabi (1988): threshold observed
- Overall width
  - Smaller influence of local disturbances
  - Future testing at TU Delft

Overall width and Effective width
Test results (1)

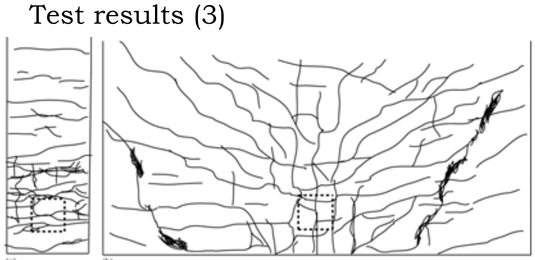


Overall width and Effective width
Test results (2)

- Threshold observed
- Calculated from series vs. 45° load spreading
  - French method: better estimate
  - Lower effective width at CS
  - Influence of size of loading plate



Overall width and Effective width
Test results (3)

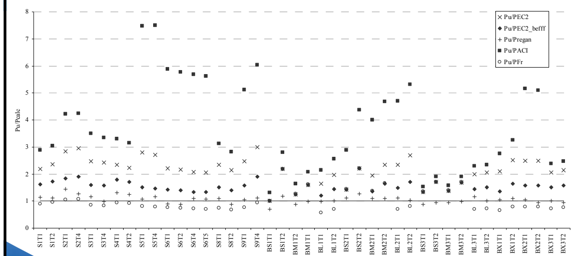


Comparison cracking pattern BS2T1 and S9T1

Comparison to Code Methods
Codes

- EN 1992-1-1:2005
  - Shear governing over punching
  - French NA: higher v_{min} for slabs (BL, BX, S)
- ACI 318-08
  - For slender beams
  - Short shear spans: strut-and-tie models or non-linear methods
  - Inclined cracking load
- Regan's method
  - Based on punching perimeter
  - Enhancement close to support
  - Enhancement for CS

Comparison to Code Methods Results (1)



ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Comparison to Code Methods Results (2)

- Regan's method
  - Best results for slabs
  - SS/CS not correct
- French National Annex
  - Overestimates capacity
- Eurocode
  - French load spreading
  - Conservative in all cases

S4T2 Dominant shear crack

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Comparison to Code Methods Results (3)

- Different behavior slabs and beams:
  - Regan: enhancement β + punching perimeter
  - Cracking pattern: change from beam to slab
  - Empirical code equations:
    - Beams
    - Small
    - Slender
    - Heavily reinforced
  - Slabs: transverse load spreading

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Comparison to Code Methods Recommendation

- Evaluating existing solid slab bridges:
  - EN 1992-1-1:2005
  - Effective width: French method
  - 25% reduction of contribution concentrated load close to support
  - $\beta = a_v/2d$

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Conclusions (1)

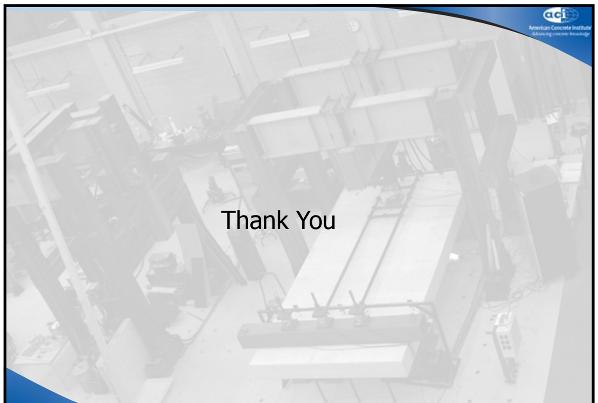
- Shear span to depth ratio
  - Smaller influence in slabs
  - 3D load spreading
- Size of loading plate
  - Influence on capacity
  - Larger influence for wider element
- Effective width
  - Threshold observed
  - French load spreading method

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Conclusions (2)

- Comparison to methods
  - EN 1992-1-1:2005, French load spreading
  - Regan: slabs
- Observation
  - Different behavior for slabs in shear

ACI WEB SESSIONS — Shear Capacity of Slabs and Slab Strips Loaded Close to the Support



Thank You

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Shear Capacity of Slabs and Slab Strips Loaded Close to the Support

Mahmoud Kamara, ACI member, is a Senior Structural Engineer at Portland Cement Association, Skokie, IL. He is involved in developing technical publications, coordinating and conducting seminars, and assisting in developing structural engineering software. He serves on several ACI technical committees and is a member of the American Society of Civil Engineers. In 1992, he received the ACI Structural Research Award.

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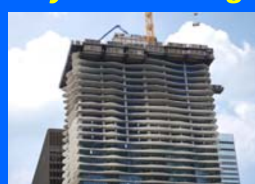
Historical Perspective on the Evolution of Two-Way Slab Design



Mahmoud Kamara, PhD
Mustafa A Mahamid, PhD, SE
Lawrence C. Novak, SE, FACI, LEED® AP

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Slab Systems Historical Review

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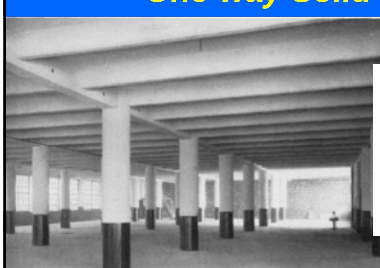
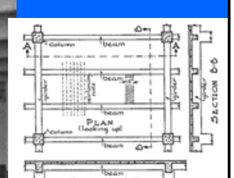
One-way Solid Slab





Complex formwork
Deep system

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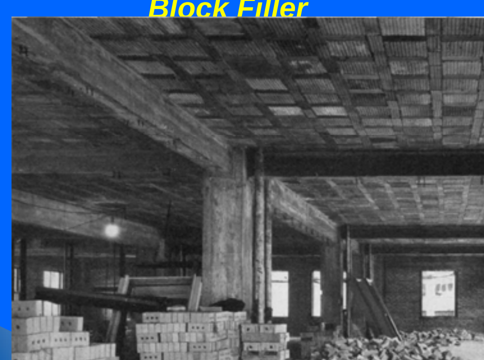
Two-way Ribbed Slabs with Block Filler



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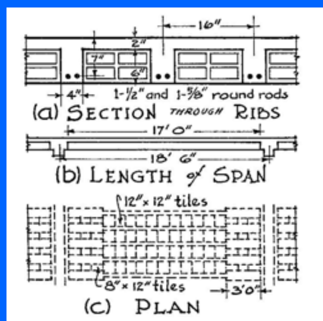
Clay Tile Filles



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One-way Ribbed Slabs with Removable Metal Pans

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One-way Ribbed Slabs with Spreader Joists at Third Points

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Girderless or “Flat Slab" Floors

Maximum story height without obstruction

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Factors Contributed to the Evolution of Two-way

- Replacement of the working-stress with the strength-design method
- Increase in the concrete and steel strengths
- Development in formwork
- Use of post-tensioning for cast-in-place systems
- Implementation of more efficient construction techniques

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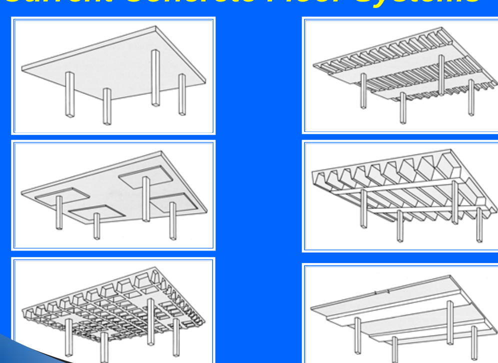
Current Concrete Floor Systems



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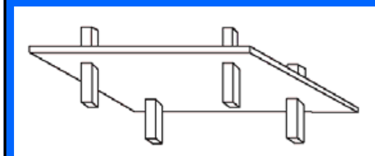
Flat Plate



Example:
Museum Towers, Cambridge, MA
- Twin luxury residential high-rise
- 8-in. flat plate
- 13 ft – 24 ft spans
- The low floor to floor heights enabled two additional floors

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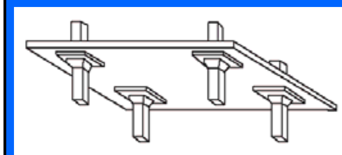
Flat Slab



Example:
Washington University School of Fisheries, Seattle, WA
- Allows ceiling space for mechanical ducts and pipes
- Inherent vibration resistance
- Seismic forces resisted by perimeter moment frame

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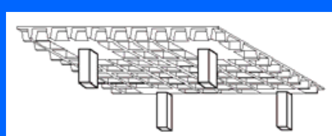
Waffle Slab



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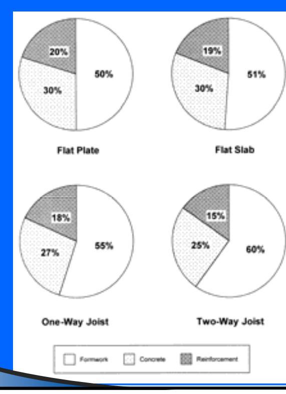
Economy of Floor Systems



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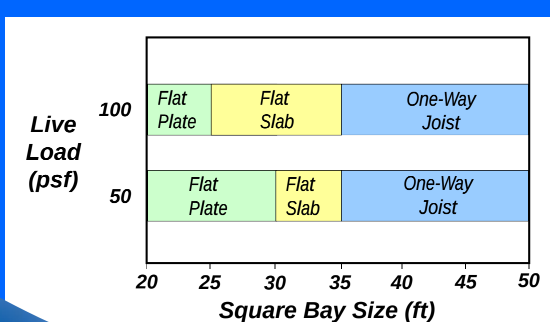
Economy of Floor Systems



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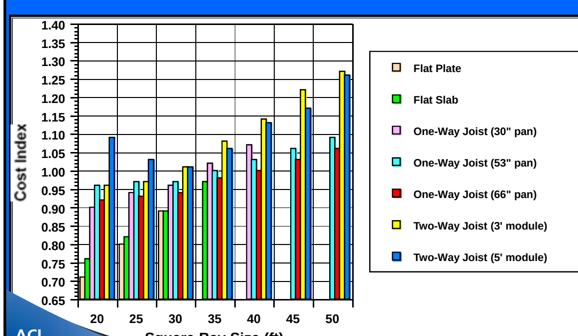
LL = 50 psf



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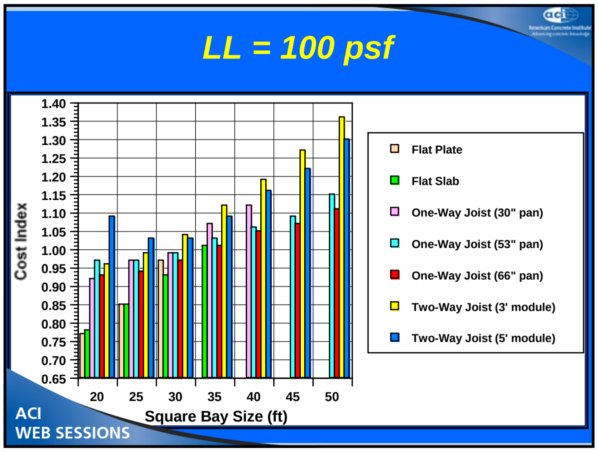
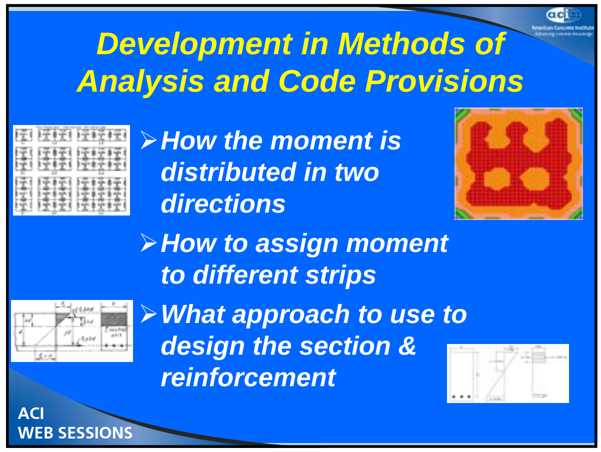
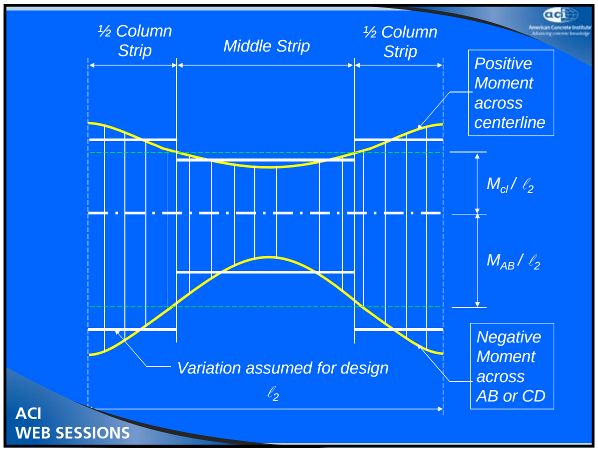






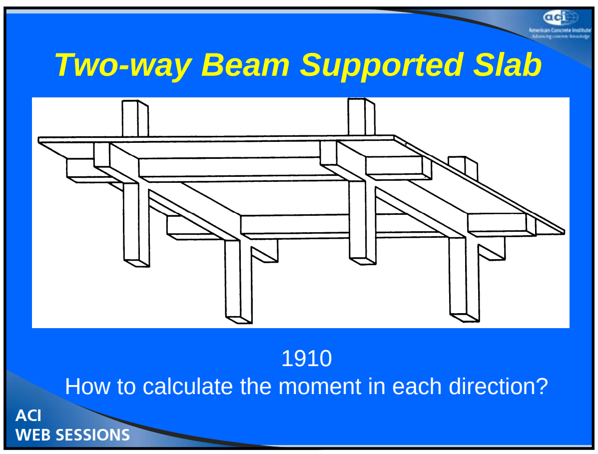

STANDARD No. 4.

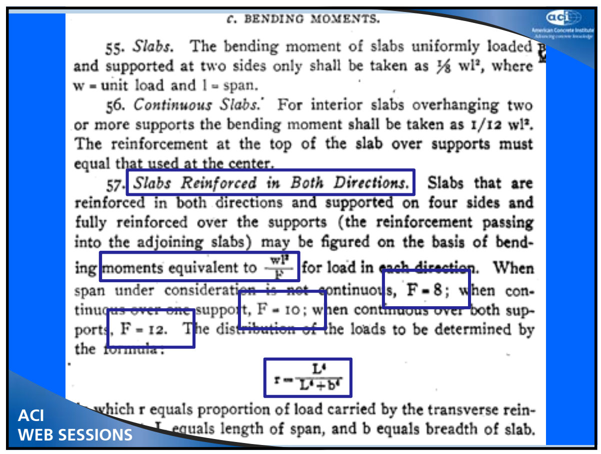
NATIONAL ASSOCIATION OF CEMENT USERS.

PHILADELPHIA, PA.

STANDARD BUILDING REGULATIONS FOR THE USE OF REINFORCED CONCRETE.

ADOPTED FEBRUARY, 1910.




c. BENDING MOMENTS.

55. *Slabs.* The bending moment of slabs uniformly loaded and supported at two sides only shall be taken as ⅛ wl^2, where w = unit load and l = span.

56. *Continuous Slabs.* For interior slabs overhanging two or more supports the bending moment shall be taken as 1/12 wl^2. The reinforcement at the top of the slab over supports must equal that used at the center.

57. *Slabs Reinforced in Both Directions.* Slabs that are reinforced in both directions and supported on four sides and fully reinforced over the supports (the reinforcement passing into the adjoining slabs) may be figured on the basis of bending moments equivalent to $\frac{wl^2}{F}$ for load in each direction. When span under consideration is not continuous, F = 8; when continuous over one support, F = 10; when continuous over both supports, F = 12. The distribution of the loads to be determined by the formula:

$$r = \frac{L^4}{L^4 + b^4}$$

in which r equals proportion of load carried by the transverse reinforcement, L equals length of span, and b equals breadth of slab.

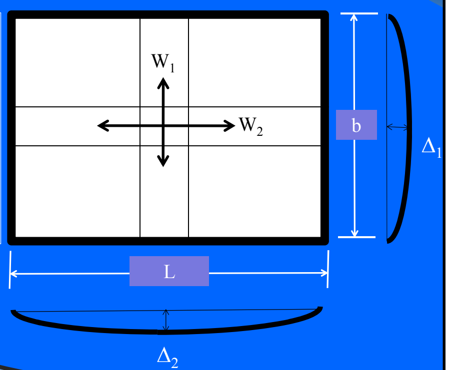
1910

$L \neq b$

$\Delta_1 = \Delta_2$

$W_1 \neq W_2$

$W_1 + W_2 = W$



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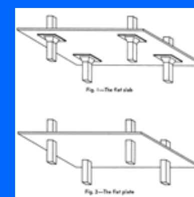
Flat slabs & Flat Plates

- *The first flat slab in Minneapolis – Turner*
- *By 1913, over 1000 flat slab buildings had been built around the world*
- *Different assumptions and design methods were used*
- *The variation in results was 400%*



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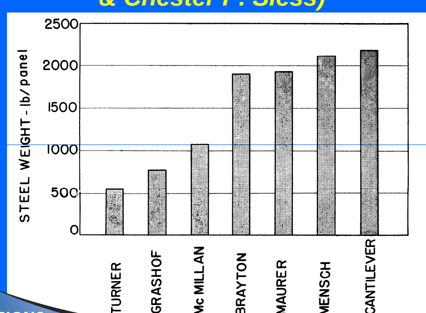
1910 Weight of Steel in Interior Panel (20'X20') using Different Designs – (Mete A. Sozen & Chester P. Siess)



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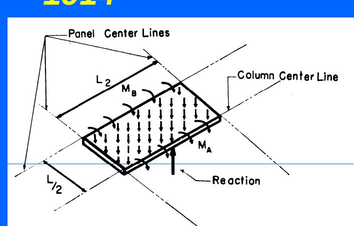
Load Testing of Two-way Slab

ACI WEB SESSIONS

J. R. Nichols 1914

- M_A & M_B
- *Reactions are uniformly distributed*
- *Twisting moment ignored*



$$M_A + M_B = M_0 = \frac{WL}{8}.$$

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AMERICAN CONCRETE INSTITUTE.

STANDARD SPECIFICATIONS No. 23

STANDARD BUILDING REGULATIONS FOR THE USE OF REINFORCED CONCRETE.*

1920

ACI WEB SESSIONS

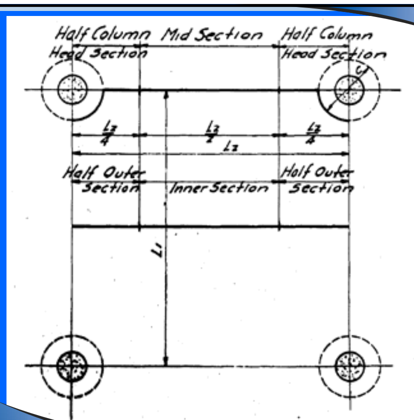


FIG. 9.

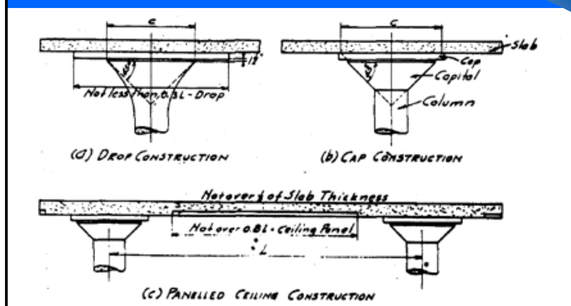


FIG. 10.

1936

No exact theoretical solution of the problem of the stresses in a series of adjacent unequal rectangular panels has yet been brought to the attention of the committee. The approximate solution embodied in this Section is believed to be conservative, but the best available.

1941 - 1956

Building Regulations for Reinforced Concrete (ACI 318-41)

Building Code Requirements for Reinforced Concrete

Building Code Requirements for Reinforced Concrete (ACI 318-51)

ACI Standard
Building Code Requirements for Reinforced Concrete (ACI 318-56)*
Reported by ACI Committee 318

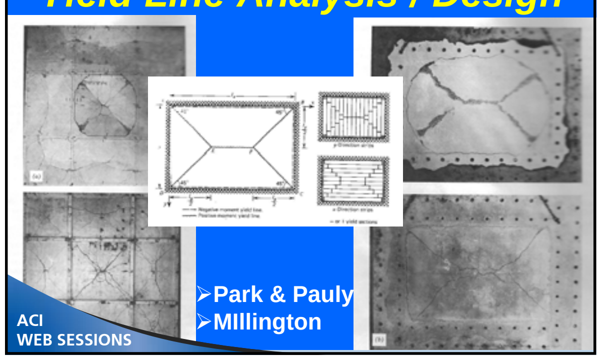
- Design of Flat Slabs by Moment Coefficients
- Design of Flat Slabs as Continuous Frames
- More Reinforcement Details

ACI Standard
Building Code Requirements for Reinforced Concrete (ACI 318-63)

COMMENTARY ON BUILDING CODE REQUIREMENTS FOR REINFORCED CONCRETE (ACI 318-63)

Attempt has been made in Chapter 21 to incorporate such items of research and progress in the art as have been acceptably interpreted at this time. Research is continuing with, for example, the multiple panel program under the Reinforced Concrete Research Council and studies by ACI-ASCE Committee 421, Design of Reinforced Concrete Slabs.

1960 – 1970
Yield Line Analysis / Design



- Park & Pauly
- MIllington

1971-2011

- Direct Design Method
- Equivalent Frame Method


ACI WEB SESSIONS

13.5.1 — A slab system shall be designed by any procedure satisfying conditions of equilibrium and geometric compatibility, if shown that the design strength at every section is at least equal to the required strength set forth in 9.2 and 9.3, and that all serviceability conditions, including limits on deflections, are met.

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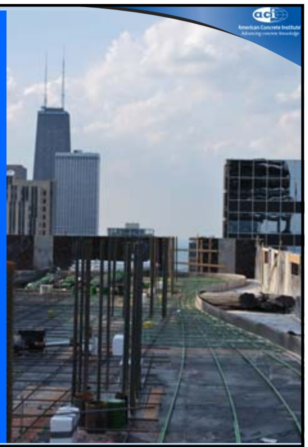

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The Ultimate Application of Two-way Slab Technology

Concrete Kitchen Countertops

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Thanks

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