YOUNG JIRSA'S YEN

by

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ABSTRACT

Engineering consensus documents in the U.S. on proportioning of reinforced concrete slabs went through creative and contradictory transformations starting in 1900's until a compromise was reached between mechanics and practice as a result of the Investigation of Multiple-Panel Floor Slabs carried out in Talbot Laboratory of the University of Illinois, Urbana, from 1957 to 1963. This paper traces the work on reinforced concrete slabs in Urbana that started with Arthur Newell Talbot and continued virtually without interruption to the time of Dr. Jirsa's arrival in Urbana to deliver the coup de grace.

Uno no tiene que ser torero para poder criticar a un matador.[2]

INTRODUCTORY REMARKS

What brought young Jirsa to Urbana, IL, from Nebraska in 1960 was a movement that started in late 19th century. In the year 1872, the engineering college catalog of the then four-year old Industrial University of Illinois brandished the message "*This school is designed to make good practical engineers*." Five years later, Arthur Newell Talbot of Cortland, Illinois, a small town 60 miles west of Chicago, arrived in Urbana, Illinois, intent on becoming an engineer. He graduated in 1881 with a degree in civil engineering and took a job in railroad construction. In 1885, he returned to Urbana as an Assistant Professor of Engineering and Mathematics. He completed his career as a Professor of Municipal and Sanitary Engineering In 1926 and continued on with his research at Urbana. His tangible contributions to the University of Illinois were the Engineering Experiment Station (1903) and Talbot Laboratory (1930). His intangible but more powerful contribution was the shaping of a way of thinking about structures that lasted over a century and produced a continuous stream of talent such as Duff Abrams, Anton Brandtzaeg, Rex Brown, Hardy Cross, Eivind Hognestad, Vernon Jensen, Ralph Kluge, Arthur Lord, Nathan Newmark,

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[2] One does not have to be a bull fighter to judge one.

Frank Richart, Chester Siess, Willis Slater, Ivan Viest, and Harald Westergaard, a torrent that ultimately produced highly competent and creative structural engineers and researchers the like of James O. Jirsa.

TALBOT

Talbot's unswerving creed was "observation uncluttered by preconception." It was indeed Talbot who fulfilled the promise of the institution to produce "good practical engineers" and initiated the approach to engineering research that survived for over a century. His influence is discernible not only in his own students but also in generations of his students' students. Talbot was still in school when Charles Peirce defined "pragmatism." Stated in engineering terms, the concept would value any theory only in proportion to its success in practice. Conversely, if the observations supported a relationship between input and output, the relationship could be used within the limits of the observations made despite the lack of first principles. One could say that in Talbot's world, as in Alexander Pope's, whatever was, was right. Very early in his career as a civil-engineering researcher, he worked on the problem of resistance to flow through locomotive water columns. He arrived at a simple expression to determine the size of the relief valve and concluded with a curt "This method has had experimental verification." That was all he said in its defense. Talbot maintained that attitude throughout his career. He took an interest in reinforced concrete relatively late in his career, after 1900's. He had kept his connections with the railroad industry. His conception of an engineering experiment station at Urbana emanated from his belief that the railroad industry, among others, needed systematic testing to solve some of their construction problems. In addition to problems related to fatigue of metals, railroad engineers had questions related to behavior of reinforced concrete. The first bulletin, published in 1904, one year after the founding of the University of Illinois Engineering Experiment Station, focused on reinforced concrete beams. It is not wasted print to emphasize the obvious. He could have named the station "The Illinois Center for Engineering Research," but he did not. To him, the proper experiment and its proper observation and reporting without prejudgment were the important goals. In what was essentially a public-relations pamphlet, Breckenridge (Breckenridge, 1906) was explicit about the goal of pragmatism. He wrote, "It is the purpose of the station to carry on investigations along various lines of engineering, and to make studies of problems of importance to professional engineers, and to the manufacturing, mining, railway, constructional and industrial interests of the state. It is believed that this experimental work will result in contributions of value to engineering science and to the industries of the state, and that the pursuit of such investigations will give inspiration to students and add to the value of the instructional work in the College of Engineering."

In 1906, C. A. P. Turner (Turner, 1909) built the first flat slab creating a strong controversy among structural engineers because Turner used only 25% of the reinforcement demanded by theoretical considerations of the time but still managed to produce serviceable and safe structures. Talbot was interested. He published his first study of the topic in 1916 (Talbot and Slater, 1916), a document that was limited to carefully qualified observations. In 1918, he had the opportunity to test a structure that was slated to be demolished (Talbot and Gonnerman, 1918). Despite the existing professional consensus that the static moment (absolute sum of negative and positive moments in a symmetrically restrained panel with circular columns) would be

$$M_o = 0.09\, WL\left(1 - \frac{2}{3}\frac{c}{L}\right) \qquad (1)$$

Talbot expressed it correctly in keeping with Nichols's statement as being approximately (Nichols, 1914)

$$M_o = \frac{1}{8}\, WL\left(1 - \frac{2}{3}\frac{c}{L}\right) \qquad (2)$$

W : Total uniform load on a slab panel

L : Span in direction considered

c : column diameter

It must have been his pragmatism that a few years later he was willing to accept Eq. 1 for design and also rationalized that the moment demand in isolated footings would be 85% of that based on statics.

WESTERGAARD

Perhaps the most important result of Talbot's interest in slabs was attracting Harald Malcolm Westergaard to come to Urbana as a graduate student. Westergaard had completed his education in Copenhagen in 1911. Advised by his teacher, A. S. Ostenfeld, to continue for a doctoral degree, Westergaard went to Goettingen and then to Munich and was about to complete his dissertation in 1915 when war in Europe made it impossible for him to continue his studies. This time Ostenfeld advised him to go to Urbana because Ostenfeld thought there was an engineer in Urbana who was doing some work on slabs, a topic in which Westergaard was interested. Westergaard obtained his PhD degree in Urbana and continued his research as a faculty member of the University of Illinois. His cooperation with Slater, another student of Talbot, led to "Moments and Stresses in Slabs," (Westergaard and Slater, 1921). This monumental work settled, at least for all well informed engineers, the controversy resulting from the apparent contradictions between mechanics and observation. In addition to demonstrating the commonalities of flat and two-way slabs in terms of plate theory, the paper was designed masterfully to appeal to the practicing engineer. The dominant discrepancy between measured and calculated reinforcement stresses was laid to rest by a simple plot that deserves mention. The influence of the tensile strength of the concrete on the moment resistance of a reinforced concrete section is by now well known under the misleading name of "tension stiffening" when the physical phenomenon is actually one of "tension softening." At moment demands below the yield moment, under static monotonic load, tensile strength of the concrete helps resist some of the applied moment so that the stress in the reinforcement, inferred from measured strain, may be well below the stress that would be required in the reinforcement to resist the moment if the calculation of stress is based on the assumption of concrete having no tensile strength. If that happened in a simply supported beam, the observer might look for explanation in other factors than in the value of the moment demand. If that happened in a two-way slab, one could be confused by the consideration that load is carried in more than one direction. As Nichols (Nichols, 1914) had demonstrated, there was no credibility to imagining that only part of the load on a slab was carried in one direction but his point of view had not met with unanimous approval of the profession possibly because the complexities of plate theory could be used to confuse. Westergaard and Slater separated the question of measured moment magnitude from theory and made their clarifying statement in a simple plot (Fig. 1) showing the relationship of measured calculated reinforcement stress in beams (where there was no question about the magnitude of moment) to the calculated stress based on the "straight-line formula." Their approach, which was admittedly indirect, convinced more engineers than did Nichols's simple and direct solution for the static moment .

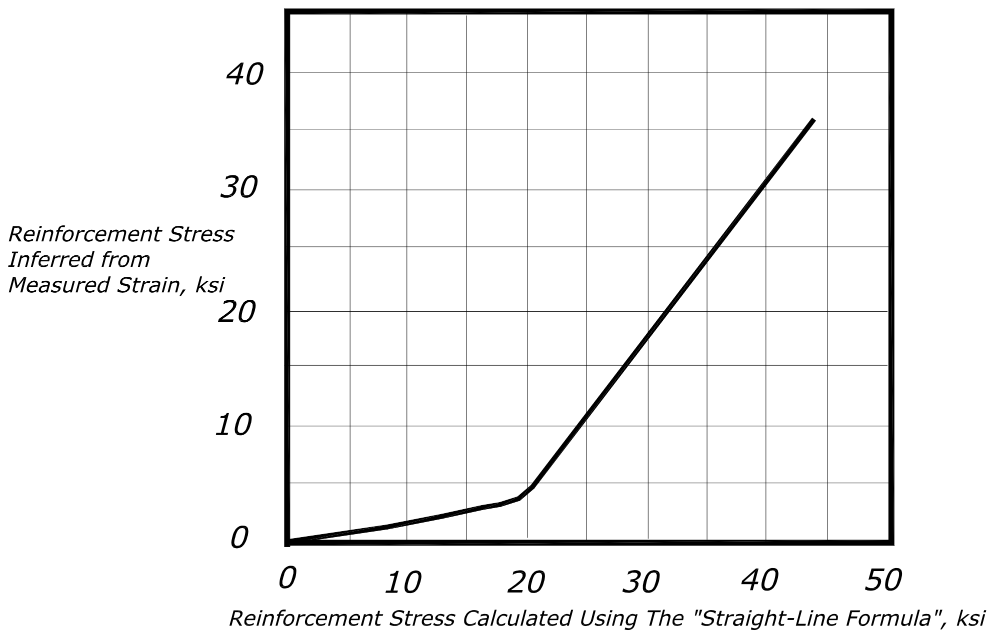

Figure 1 Relationship between "Measured" and Calculated Reinforcement Stress in A Beam

Westergaard and Slater presented a plot of moment distribution in a square interior panel of a flat slab that may be one of the best examples of graphic art in engineering expression. An abbreviated version of their illustration is shown in Fig.2. The useful information packed in their figure matches the celebrated drawing, by another civil engineer (Charles Minard), providing data on Napoleon's 1812 trip to and from Moscow (Tufte, 1984).

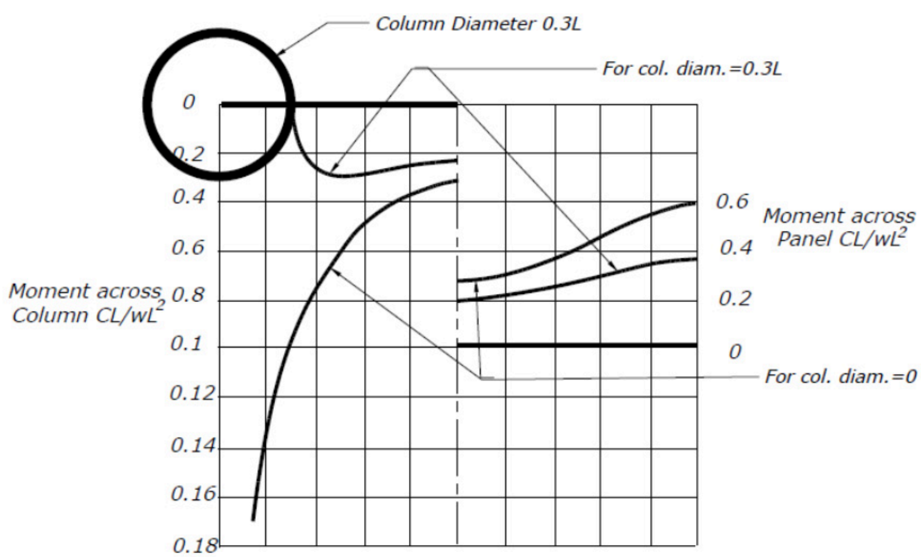

Figure 2 Partial Reproduction of The Moment-Distribution Plot by Westergaard and Slater

Westergaard and Slater went beyond the extensive information given in their version in Fig. 2 After confirming Nichols (Eq. 2) by defining the static moment, M_o , (absolute sum of the positive moment and the mean of the negative moments at each support in one direction) as he did, they went on to propose a very simple table to help designers determine how to distribute the reinforcement in an interior panel (Table 1) .

TABLE 1

	Percent of Static Moment, M_o		
	Column Strip (Width = Panel Width/2)	Middle Strip	Total
Moment at Support	48	17	65
Moment at Mid-Span	21	14	35

CROSS

Hardy Cross, who joined the faculty in Urbana in 1921, wrote that one could proportion two-way slabs simply by considering ".. the limitations imposed by statics upon the total moments, principles of symmetry and asymmetry, and mental pictures of the deflected slab as a means of judging of the variation of the moments along any given section….. The writer finds the idea of distributing fixed-end moments useful in revising his mental pictures of the deflected slab as a means of judging of the variation of the moments when affected by continuity with other slabs or by discontinuities." It took Ingerslev (Ingerslev, 1921) to state the basic rules of yield-line analysis, Johansen (Johansen, 1931) to generalize the rules, and Hognestad (Hognestad, 1953) to translate their work to English for the majority of the profession in the U.S. to appreciate Cross's wisdom on proportioning of slabs (Cross, 1929).

NEWMARK

The momentum of interest on analysis of slabs picked up again in Urbana in the 1930's as a result of the cooperative efforts of Westergaard and Cross. For cases where classical closed-form solutions did not apply, Westergaard had used finite-difference solutions, his own and those of others. Nathan M. Newmark, a student of Cross and Westergaard who had joined them on the faculty, was interested in combining the two engineer's approaches to bring about a pragmatic and general approach to design of two-way slabs. Without the computational tools we enjoy today, he was at a disadvantage for obtaining finite-difference solutions to cover a sufficient number of cases. His disadvantage became an advantage because it drove him to think. He projected Cross's brilliant and simple solution for frames to apply to slabs (Newmark, 1938). His work was inspired by Cross's creativity and influenced by Westergaard's talent to simplify the complex. Because the dominant thinking of the time on structural design was focused on bridges[3] that were sensitive to pattern loading and because the design criterion was working stress, his focus was on effects of pattern loads on moments in slabs in the linear range of response. Newmark's 1938 opus was influenced by problems related to slabs in bridges. Later, working with his student Chester P. Siess, Newmark shifted his attention to floor slabs in buildings. Their work resulted in a paper (Siess and Newmark, 1948) published in the Journal of the American Concrete Institute with the title "Rational Analysis and Design of Two-Way Concrete Slabs." From the title, it might be inferred that they had deviated from the path set by Talbot, but it was not so. As stated explicitly in their paper, the method they proposed was "not exact since the values of the stiffness and carry-over factors can be determined only approximately." As Talbot would have approved, they recognized the need for tests to calibrate their conclusions and emphasized that they had no directly relevant test results. Their conclusions were based on analytical studies. The paper identified the dependence of stresses in two-way slabs (slabs supported by beams on all four sides) to three factors as well as the magnitudes of the load and the span: (1) relative flexural stiffness of the beam to that of the slab, (2) relative flexural stiffness of the column to the combined flexural stiffness of the slab and the beams, and (3) torsional stiffness of the beams.

[3] Because of the dominance of working stresses in design, Siess and Newmark concentrated on the effects of pattern loadings, undeniably a mode of thinking heavily influenced by the preoccupation of the structural-design profession with bridges in the early part of the 20th century

SIESS

The moment distribution method developed by Newmark was extended by Siess and provided the analytical platform for their extensive analysis of the effects of span, load, panel shape, beam flexural stiffness, beam torsional stiffness, and slab flexural stiffness. Despite their explicit consciousness of nonlinear response, of redistribution of moments within the slab and from slab to beam, their quantitative conclusions were influenced by moment-demand changes calculated for linear slabs and beams, that would be caused by pattern loadings. They studied and compared the effects of checkerboard and single-panel loadings with those of uniform loading. They investigated the effects of beam deflections. Although they related safety to effects of pattern loadings because they were operating in the realm of working stress design, that they had not deviated from the Talbot tradition was evident when they stated that a difference as much as 28% between the design moment and the actual could be tolerated.

Newmark and Siess started pushing the bounds set by professional consensus committed to the criticality of pattern loading. Pointing out the discrepancy in design documents leading to a wide difference between the influences of pattern loads in flat slabs and two-way slabs, they showed that typically a monolithic reinforced concrete beam has sufficient torsional stiffness to ameliorate the effect of checkerboard loading and that, to obtain a satisfactory measure of the effect of pattern loading, it was sufficient to consider single-panel loading for most cases.

Even though Newmark and Siess had named their first paper "Rational Analysis and Design of Two-Way Concrete Slabs," it was clear that their emphasis was on design as they started by stating how approximate their numbers were and named their second paper "Proposed Design Specifications for Two-Way Floor Slabs." The two papers were quite influential. They convinced the leadership of the structural engineering profession that an organized study was due for the way slabs were considered in design. Indeed, slabs did not constitute the critical elements of the entire structure but they required as much material as the main elements.

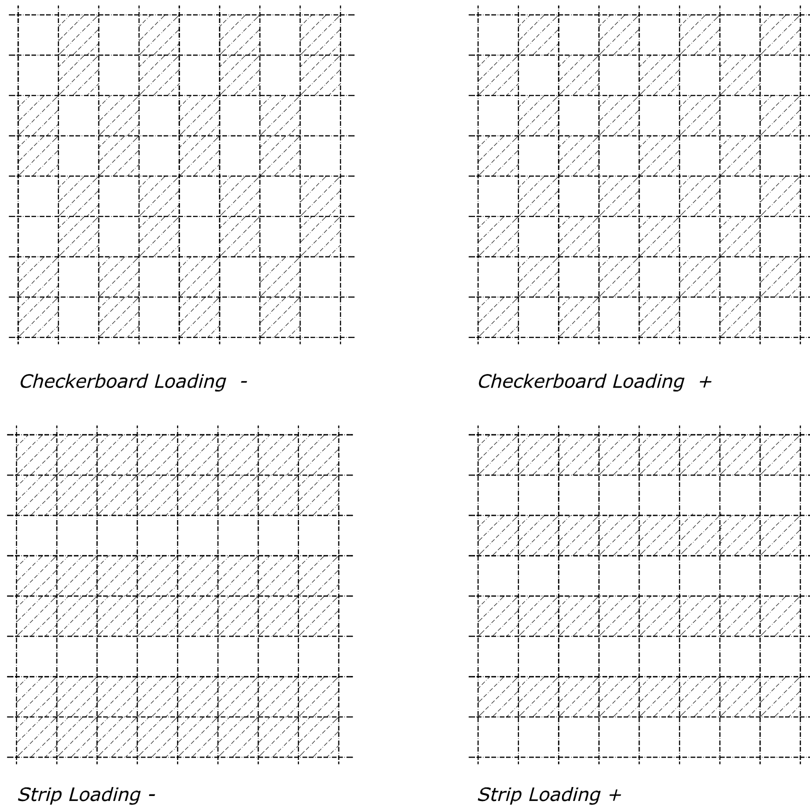

Figure 3 Checkerboard and Strip Loading Patterns Shown for One Direction

In 1957, a broad-front research program led by Newmark and Siess was initiated at Talbot Laboratory of the University of Illinois incorporating both analytical and experimental work (1963). The program had an advisory committee of academic and professional engineers. A total of five multiple-panel slabs (each with nine panels) were tested under gravity loads. The typical test program for each structure comprised a series of strip and checkerboard loadings to the service-load level followed by a test to failure with all nine panels loaded.

JIRSA

Young Jirsa found himself, as a graduate student, in charge of testing the last specimen. Many of the experimental challenges had been solved including the use of automated recording of strain gages (alas on "punch cards"), but the use of reinforcement with a fracture strain below 6% had yet to be understood. Jirsa completed the fabrication and testing of the structure in record time and showed his talent in dealing with the unexpected when he found out that linearity of strain over the depth of the reinforced concrete section was a fiction maintained traditionally because typical reinforcement used in reinforced concrete structures had a large strain capacity, on the order of a hundred times the yield strain.

After his successful completion of the flat-plate structure with welded wire fabric for flexural reinforcement in the slab, young Jirsa's yen was to simplify if not eliminate the pattern-load problem that tended to complicate design analyses for slab. He was going against professional faith. He had the experimental data from five test structures and the analytical background provided by Newmark and Siess. The challenge was to simplify design. As Vachel Lindsay might have said, young Jirsa was influenced by Talbot, Westergaard, and Cross who stalked the corridors of Talbot Laboratory at midnight. Simplicity was more important than precision. If one was going to be wrong anyway, one might as well be wrong the easy way. Young Jirsa, steeped in the intellectual environment in Urbana, knew that analyses used for design did not necessarily have to predict response. The primary object of design was to obtain a safe, serviceable, and economical structure. Above all, the design method should enable the designer to estimate the result before implementing the method and not hide the outcome. He had read Cross who wrote about slabs, "Analyses indicate certain distributions of reinforcing steel [in slabs], whereas often quite different distributions are just about as effective. No one has pointed this out more clearly than Westergaard (Cross, 1936)."

Young Jirsa did not fail his heritage. First, he observed that the expected variations caused by pattern loads in slab moments at the edges of supporting beams would be in a tolerable range and could be safely ignored in design. By focusing on positive moments, more than half the problem had been elimninated. He invented a different way of sensing the effects of the dominant parameters by combining them in three ratios as follows:

Beam Flexural Stiffness

$$\frac{H}{1+H} \qquad (3)$$

$H_a = \dfrac{EI_a}{b\frac{Et^3}{12}}$ in direction a