# Investigation of a Sheffield Structural Tile Floor Failure Indicates a Dangerous Design/Development Oversight

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**Abstract:** The Sheffield Brick and Tile Company produced a series of structural tile units that were used to construct floor and roof decks. The tiles were used as integral components in composite concrete, tile, and reinforcing bar deck systems. After roughly 40 years of service, the Sheffield Tile Deck System (STDS) in a school building failed. Investigation of the failure provided a clear indication that the design/development process overlooked a potentially critical feature of these systems. The investigation also revealed a mechanism whereby an STDS could provide adequate service, then fail in a rather abrupt fashion. During the investigation, reports of other STDS failures were discovered, including some referenced in Sheffield Brick and Tile Company correspondence to an owner of a STDS, suggesting he have it checked out by a qualified engineer.

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## Introduction

For many years, the Sheffield Brick and Tile Company of Sheffield, Iowa, produced structural tile units that were used in conjunction with concrete and reinforcing bars to build structural floor and roof decks. A typical Sheffield Tile Deck System (STDS) consisted of an essentially solid array of tile units, covered with a cast-in-place concrete topping. Reinforcing bars were incorporated via channels in the bottoms of the tile units. A schematic transverse cross section through an STDS is shown in Fig. 1.

Construction of an STDS began by forming longitudinal (parallel to the reinforcing bars) rows of upside-down tiles, so that the rectangular grooves in the bottom of each unit formed a continuous channel. A reinforcing bar was then grouted into the channel, forming a rather flexible, prefabricated tile plank. A series of planks would then be placed side-by-side to create a solid tile deck. Each end of each plank would rest on a supporting wall or beam, while temporary shoring would provide intermediate support. After all the tile planks were place, a concrete topping would be cast onto the top of the tile deck.

Although, in many ways, an STDS is similar to a one-way concrete deck made up of concrete-topped, precast concrete planks (e.g., a hollow-core system), there are significant differences. In the context of this paper, the most significant difference relates to the configuration of the respective web elements. The web elements in a precast plank are essentially continuous. In contrast, the web elements in an STDS (the vertical portions of the tile units) are discontinuous at every tile/tile interface (every 12 in.). As will be discussed herein, these closely spaced discontinuities influence the stresses created in the tile units when the deck is loaded to the extent that common methods for assessing web integrity are not applicable.

## Background

In March 2000, an STDS comprising a classroom floor in a school facility began to deflect rapidly, accompanied by loud cracking noises. After a period of several hours and after sustaining displacements of several inches, the floor apparently stabilized. A photograph of the underside of the floor at this time is shown in Fig. 2. After a period of several weeks, a portion of the floor system fell onto the floor of the room below. A photograph of the collapsed area is included as Fig. 3.

At the time of the failure, the floor system was roughly 40 years old and had been an interior component of a well-maintained building. Immediately prior to the collapse, the STDS was free of any apparent damage or distress. At the time the failure began, live load was limited to several partially filled bookshelves (mostly along the perimeter of the room), a few pieces of classroom furniture, and some students. The soffit of the STDS was covered with a layer of plaster.

Several years before the subject floor failure, the roof of the school's cafeteria (also an STDS) reportedly collapsed suddenly, and without prior indication that it was not stable. Other instances of STDS failure have been reported in newspaper articles. The Sheffield Brick and Tile Company also wrote to at least one party that had STDS roof and/or floor decks, referencing reported problems with systems in other facilities "many years after installation" and suggesting to the owner that "you engage a qualified engineer to check out the installation so that you can be satisfied the structure is still sound." The investigation outlined in this paper indicates a fundamental problem with the design/development of the STDS.

## Floor System Details

Examination of the subject STDS revealed the following characteristics:

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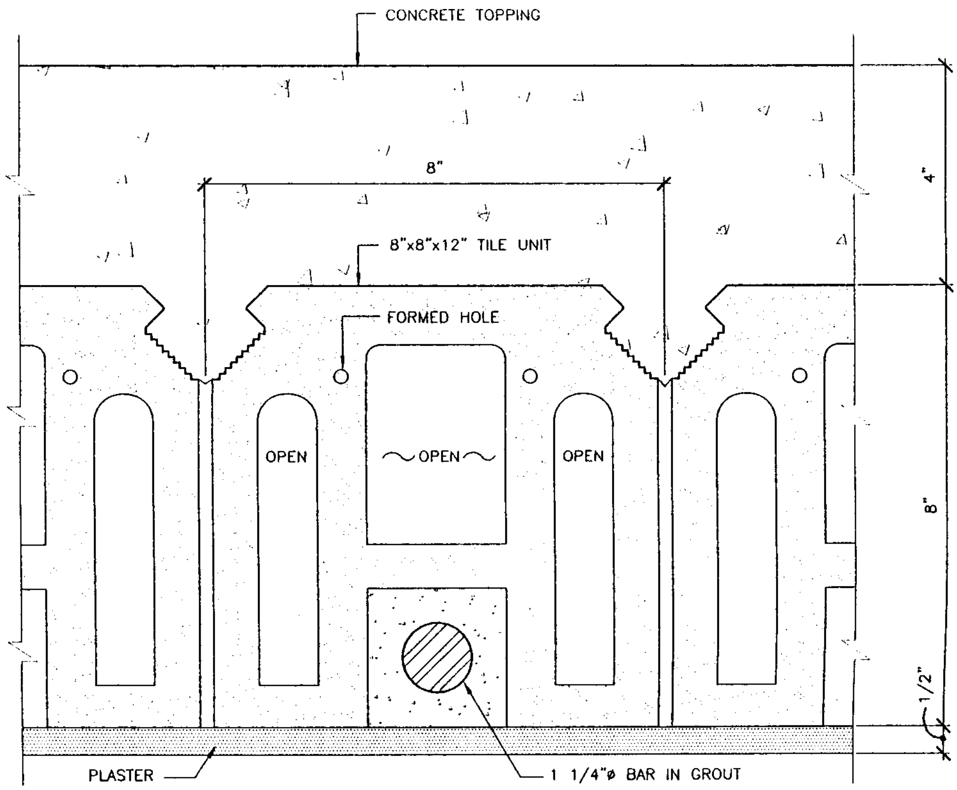


**Fig. 1.** Transverse cross section

- Clay tile units with the words ''Sheffield Load Bearing Tile'' on the sides,
- Cross-section properties shown in Fig. 1,
- A clear span of approximately 31 ft 2 in. between supporting concrete block walls, and
- A standard tile unit length of 12 in., with one transverse row of units that were about 4 in. long. The row of shorter units was located near one of the bearing walls.

Inspection of the room above the failed floor indicated a modest live load. As shown in Fig. 4, the room contained several bookshelves, primarily arranged around the perimeter, and a few pieces of furniture (several computers and computer tables had been removed before the photographs comprising Fig. 4 were taken). It was reported that, at the time the floor started to sustain large deflections, it was also occupied by a small number of students and one teacher.

The STDS details observed at the failure site were compared with the information provided in Sheffield's own Architect's Data Book. This comparison revealed conformance with Sheffield's requirements for use of their system. Furthermore, the load tables included in this Sheffield publication indicated an ultimate floor capacity that was several times the loading that existed at the time of failure.

Several core samples were taken through other floors (of identical construction) in the building. Examination of these cores and the holes they came from revealed the following:

**Fig. 2.** Underside of sagging floor

**Fig. 3.** Collapsed area

**Fig. 4.** Room above failed floor

- The concrete topping appeared to be sound and reasonably well consolidated. It also appeared to consist of normal weight material with an estimated compressive strength in the range of 4,000 psi.
- The tile units contained many planar voids that were oriented roughly parallel to the nearest finished surfaces. Examples of these voids can be seen in Figs. 5 and 6.

After observing the extent to which planar gaps were present in the tile units, and recognizing the importance of the tensile capacity of the tiles in affected areas, as will be discussed in the following section, field testing was performed to estimate the tensile strength of the tile material. These tests included the following steps:

- Coring through the concrete topping and part way into the top of a tile unit,
- Adhering a round steel block onto the surface of the cored concrete, and
- Applying an upward load to the steel block until the cored sample broke free.

A typical test sample is shown in Fig. 6. This testing indicated a wide range in tensile strengths. At the low end were the samples that were loose after coring (tensile strengths of essentially zero), while the cores that could sustain a test load indicated tensile strengths between 80 and 160 psi.

As indicated in Fig. 3, the failure of the floor did not involve a loss of bond between the concrete topping and the tiles. There was also no indication of bond failure at either the reinforcing bar/grout or the grout/tile interfaces. The tile units represented the only failed components of the STDS, with the majority of the tiles exhibiting failure near the junction between the web elements and the top flange.

## Structural Analyses

Measurements of the STDS components and tributary items indicated a total equivalent uniform load of about 115 psf at the time of the collapse. For a typical 8-in.-wide, one-tile strip, this load-

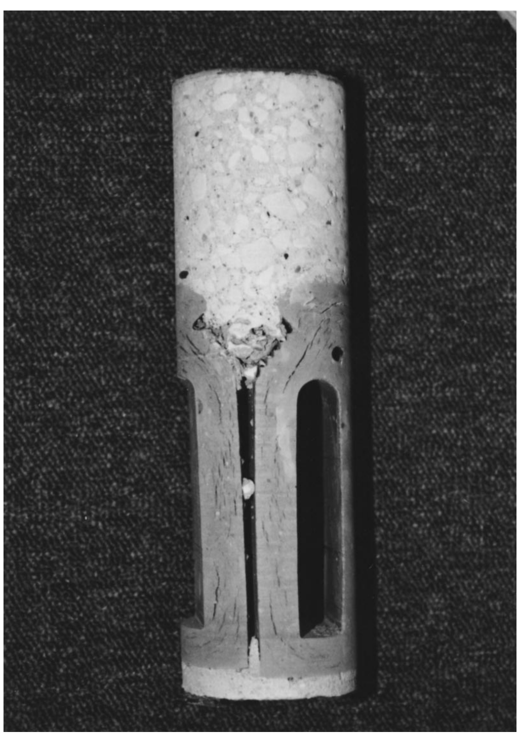

**Fig. 5.** Core through intact floor showing voids in tiles

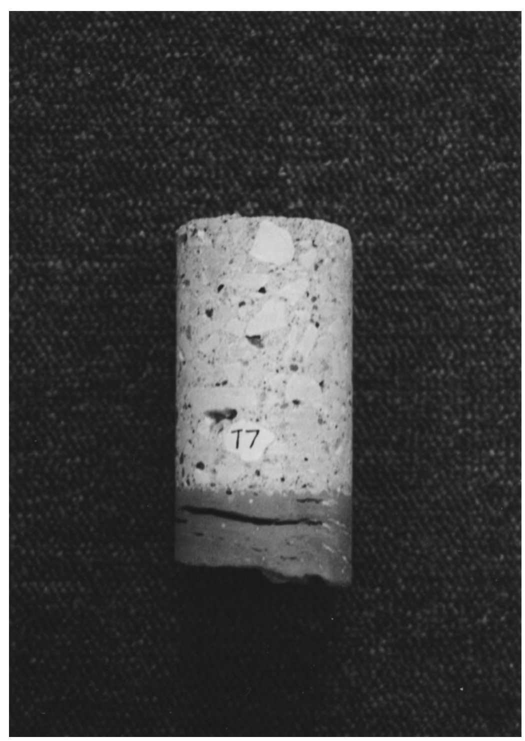


**Fig. 6.** Partial core showing large planar void in tile

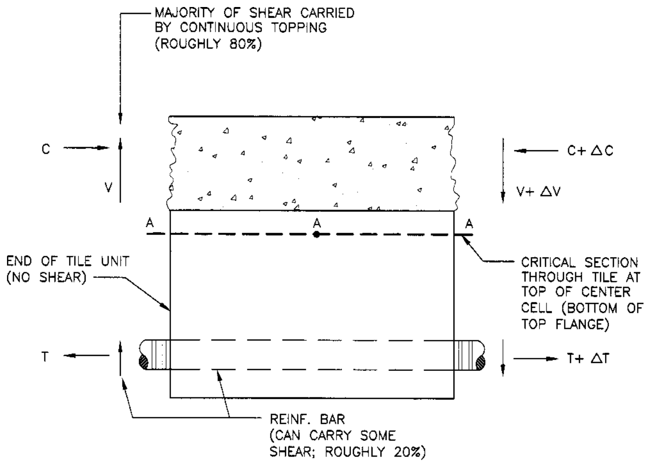


**Fig. 7.** Free body diagram of single tile section of floor

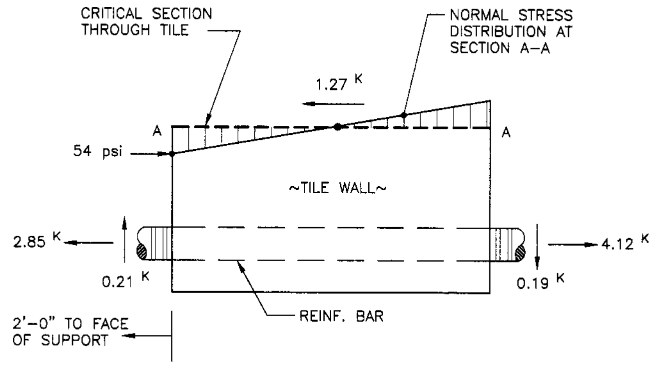


**Fig. 8.** Free body diagram below critical section

ing produces a maximum vertical shear of about 1.2 kips at the supports and a maximum moment of about 110 inch kips at midspan. Given such a load, the maximum calculated stresses in the concrete topping, the tile/topping interface, the reinforcing steel, the steel/grout interface, and the grout/tile interface are all well within corresponding expected elastic limits. These findings are consistent with observations that failure of the floor did not originate in the items listed.

In the failed floor system, the purpose of the clay tile units was to provide separation and load transfer between the concrete topping and the reinforcing steel. To make an analogy with a beam or girder, the tiles acted like the web, separating and balancing the forces between the compression flange (in this case, the topping) and the tension flange (in this case, the reinforcing steel). Unlike the web of a conventional beam or girder, however, the tiles did not act as the primary carriers of vertical shear forces. They were prevented from doing so by the full-height discontinuities at every end-to-end joint (i.e., every 12 in.). Therefore, at these locations, vertical shear forces in the STDS had to be carried by a combination of the topping and the reinforcing bars. More importantly, each end of a tile unit would be shear free, unlike their counterpart vertical surfaces in a conventional beam, which would carry almost all of the vertical shear acting at the cross section.

A free-body diagram of a 12-in.-long section of a one-tile-wide strip of STDS is shown in Fig. 7. As indicated, the vertical shear acting on each end is carried primarily by the topping, with some shear taken by the reinforcing bar. The relative shear values shown were based upon the relative shear stiffnesses of the topping and associated bar. The point to be made is the fact that the vertical shear acting through the tile (the portion taken by the bar) is much less than the total shear (which is essentially the shear taken by a conventional beam web). A significant effect of this unusual distribution of free-body forces can be seen by summing moments about the underside of the top flange of the tile (point A on Section A-A). An example based on the estimated free-body forces that existed immediately preceding the collapse, on a section of floor located between 2 and 3 ft from a supporting wall, is provided in Fig. 8. As indicated in Fig. 8, the tile walls sustain substantial vertical tensile stresses along the horizontal plane that intersects point A—stresses that would be insignificant if the walls of the tile were not discontinuous. In contrast, if shorter tile units were used, the tensile stresses in the wall elements would be greater in magnitude than those shown in Fig. 8. As indicated previously, one transverse row of tiles located near one end of the failed floor consisted of units that were only 4 in. long. Furthermore, the tile tensile stresses shown in Fig. 8 were calculated assuming the tile walls were solid. Given the fact that core samples showed that the walls contain extensive planar discontinuities in the critical areas, actual stresses immediately preceding the collapse were almost certainly much higher at most locations where similar shear forces were present.

While the general force transfer mechanism shown in Figs. 7 and 8 applies at virtually every location in a particular STDS, the magnitude of the vertical tensile stress is proportional to the difference between the reinforcing steel tension forces acting at each end of the tile. In other words, the local tile wall vertical stress magnitude is proportional to the global moment gradient, which in turn is proportional to the global shear force. Based on the analysis results summarized in Fig. 8, several wall/flange tile fractures would have been expected in the subject floor as soon as the construction shoring was removed. Although these fractures would have been concentrated primarily in the higher shear areas, near the supporting walls, tensile stresses sufficient to fracture the weakest tiles probably occurred several feet from any support.

The analysis outlined heretofore represents a model of the short-term elastic performance of the subject STDS under load, and it provides a rational explanation of why some tile walls most probably fractured under modest service loads. However, this elastic model provides no explanation why a floor system would fail rather quickly after 40 years of problem-free service. The most common reasons for structural failure after long periods of service include deterioration, damage, and overload. In this particular case, the floor system appeared to have been free of structurally significant deterioration or damage, and there appeared to be nothing exceptional about the loading. In other words, immediately prior to the failure, the floor system appeared as sound as when it was first put into service. Therefore, the change or changes that rendered it unstable must have been internal.

For a given loading, the compression force in the topping and the tension force in the reinforcing steel at any cross section are equal in magnitude and opposite in sign. This situation is shown in Fig. 7. In addition, for a particular loading, the magnitude of the compression and tension forces at a given cross section is a function of the vertical distance between their respective points of application. If this distance were to decrease while all other things remained constant, the magnitude of the compression and tension forces would increase proportionally. Furthermore, any increase in reinforcing bar tension would cause a proportional increase in the tile wall tension stresses.

In an STDS, there are at least three mechanisms that, over time, would cause the centroid of the topping compressive stress to move down, closer to the reinforcing bar. The first two involve the well-known phenomena of shrinkage and creep. In an STDS, both shrinkage and creep of the topping would result in a lowering of the compression stress centroid and proportional increases in reinforcing bar tension and tile wall tensile stresses. The relative stress increase mobilized by these phenomena may be on the order of several percent and could lead to additional tile fractures. However, the vast majority of shrinkage and creep strain would be realized within a few years of construction. Therefore, if a floor fails in this time period, these factors may be the primary causes of postconstruction tile failures, but shrinkage and creep effects alone cannot explain failure after a 40-year service life.

The third mechanism that could cause a significant shift in the compression stress field in an STDS is clay swelling. Fired clay products absorb atmospheric moisture over time, causing them to increase in volume. Any lengthening of the tile units in an STDS would cause the compressive stress field to shift downward, especially if the top flanges of the tiles were in tight contact (a common situation, because topping material typically filled the gaps between the top flanges of adjacent tiles). In the extreme case, tile swelling would be sufficient to cause the topping to crack, which would clearly place the centroid of the compression stress field in the top flange of the tile. Such a shift could result in peak tile wall tensile stresses that exceed initial values by more than 30%. Furthermore, this volume change phenomenon can occur over decades. Therefore, the combined action of shrinkage, creep, and tile expansion could cause a slow progression of tile failures such that instability would occur after 40 years of service.

The final aspect of the failure mechanism that warrants some elaboration is the suddenness with which it occurred. This is easily understood when it is remembered that failure of the system was caused by failure of the tiles, which are very brittle elements. This means that, if a tile is overloaded, it lacks the ability to deform in a ductile fashion as load gets redistributed to other tiles, which is the type of response that allows some systems to sustain noticeable deformations before they fail. Therefore, as long as there remained sufficient tiles to carry the imposed forces, the STDS could sustain occasional tile fractures without experiencing large deflections. But, as soon as the ''critical'' tile fractured, causing a stress increase that the next tile could not sustain, and so on, tile fractures occurred rapidly, composite action between the topping and the reinforcing steel was compromised, and large deformations occurred.

## Discussion

In spite of essentially complete conformance to the manufacturer's requirements, the subject STDS failed while carrying a small fraction of the published load capacity. The primary reason appears to be the failure of the product's developer to recognize the significance of the closely spaced vertical discontinuities in the tile walls. Had the significance of these joints been considered, the system could have been modified to keep tensile stresses within reasonable levels. For example, longer tile units could have been made for use in regions of high shear; tiles could have been manufactured with key ways or corrugations at the ends to provide shear continuity; cells in high shear regions could have been filled with grout; or the load tables could have simply been modified to only allow configurations with acceptably low shear and tensile stresses.

Unfortunately, the Sheffield publications promoted construction of floor and roof systems in which tile fractures would be expected under small fractions of the listed load capacities. As demonstrated in the evaluation of the subject failure, this includes system spans in the 30 ft range, which are very common in many types of construction. For a given cross section, longer spans are more critical. The cafeteria roof that collapsed earlier at the same facility was of nearly identical construction and had a clear span of about 34 ft.

## Conclusions

Due to an apparent design oversight, certain installations of Sheffield Tile Deck Systems do not have the strength that was intended, and in some very common applications, the discrepancy between published and actual strengths can be very large. Due to the sensitivity of the system to long term volume changes in the constituent materials, and due to the brittleness of the most likely failure mechanism, failure of a well maintained STDS may only occur after many years of service, and in most cases, will be quite sudden. Structural engineers who are asked to evaluate or otherwise render opinions concerning Sheffield systems should be very careful, especially if an evaluation concerns a proposed change of use involving increased floor loads. For example, a ''conventional'' flexure and shear check (i.e., one that does not consider the effect of the tile discontinuities) may indicate a live load capacity well in excess of 100 psf, while a much smaller load would cause failure via tensile fracture of the tiles. If such an evaluation convinces an owner to use an old classroom or office building (which survived due to very small live loads) as a warehouse, actual floor loads may be increased 10 fold, with disastrous results. Engineers should also avoid the temptation to be impressed by many years of problem-free service. As indicated herein, outward appearances can be deceiving, and an apparently intact system can be on the brink of failure.

Those asked to evaluate an STDS should, at a minimum, estimate the tile wall tensile stresses for various load configurations and compare them to actual strengths, preferably from tests on specimens taken from the floor in question. Furthermore, when test data are used to establish an allowable or useable strength, the variation in tensile strengths and the brittle nature of the failure mode warrants the use of a rather large exclusion or confidence limit. In other words, because the tile fracture failure mode lacks the ductility to mobilize the full capacities of the various tile walls (unlike a failure mode involving reinforcing bar yielding, in which bar ductility enables mobilization of the yield strength in every bar, even if some reach yield well before others), stresses in the tiles should be maintained at a relatively small fraction of the average ultimate strength.

Another item to be wary of is the use of short tiles (required to make up certain spans) in areas of high shear. When calculating critical tensile stresses, such tiles should be evaluated.

If an STDS is evaluated and believed to be deficient, there are ways to improve capacity. Perhaps the most effective measure would be to reduce the span, which can be accomplished using either intermediate load-bearing walls or structural framing. However, it is important to remember that simply installing the supplemental support in snug contact with the STDS may not be adequate. If the original system is close to failure (i.e., if a critical number of tiles have either fractured already or are close to fracturing), modest additional load, even acting over shorter spans, could cause many additional tile fractures. It may be wise to install supplemental supports so that stresses in critical areas of the original deck are reduced. Grouting cells in high stress areas may also be effective. Again, it may be necessary to unload the deck using shoring and jacks, while the grout is placed and while it cures.