Application of Plastic Design in Steel Table Shelters

by

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Abstract

One of the initial applications of plastic theory of structures was the Morrison Shelter, an indoor air raid shelter designed by John Fleetwood Baker (1901 – 1985) during the Second World War to protect British civilians from unrelenting German air raids. Baker integrated his previous work on plasticity of steel frames into the design of Morrison shelters that employed ductility and continuity, which are key principles of plastic theory. Although Morrison Shelters have been praised for their life saving capability and use of plastic theory, a technical analysis of its design process has been lacking from the historical record. To explore the use of plasticity in the Morrison Shelter’s design process, the Baker Papers stored in the Churchill Archives Centre were searched. From these materials, the impact of plasticity on the efficiency of steel frames was critically investigated. This study quantifies the savings in steel due to the use of plastic theory in the design of the Morrison Shelter. The value of savings, which was particularly significant during wartime scarcity, has been previously stated without showing technical verification.

The Morrison Shelter’s design objectives are still relevant today, particularly in developing nations where the use of plasticity to design steel table-shelters can protect school children in areas of high seismic vulnerability by providing shelters in the form of lightweight steel-framed school desks. The investigation of the concise, plastic calculations used to design the Morrison Shelter serve as inspiration for replication in future applications that need lightweight, simple structures that expect to experience impact loads.

Thesis Supervisor: John Ochsendorf
Title: Class of 1942 Professor of Civil and Environmental Engineering and Architecture
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1 Introduction

The Morrison “table” shelter, designed by Sir John Fleetwood Baker (1901-1985), was an indoor air raid shelter used as domestic protection during World War II. The significance of these shelters was two-fold: it protected civilians while serving as an early application of the developing plastic theory. Additionally, the shelters were successful because they were designed with users’ comfort and needs in mind; they served as household furniture while simultaneously protecting their occupants. The published materials on the design process of the Morrison Shelters do not fully demonstrate the technical methods employed. This thesis focuses on the influence of plastic theory in the design process of single-portal, steel frame structures, specifically, the significance of plasticity in the early application in the Morrison Shelter.

1.1 Background

1.1.1 Historical Context of Shelters

The following section provides the historical context that led to the creation of the Morrison Shelter, which was first distributed to British civilians on March 27, 1941. The Morrison Shelter was designed in response to the flaws of existing air raid shelters that were used in the Second World War.

During the First World War, London was not prepared to protect civilians from the German aerial attacks of 1915. Londoners took shelter in public, underground train stations. Although these air raid attacks were deadly, with an estimated 670 deaths
(Jones, 2006), they did not inspire engineers to consider blast performance in the design of their buildings (Cowan, 1979).

Between the wars, the British government strove to find an alternative to public shelters, which were overcrowded and negatively affected citizens’ morale (Jones, 2006). In response, they provided domestic shelters, called Anderson Shelters, to households that earned an annual income less than £250. Designed in 1938, the Anderson Shelter was named after the current Lord Privy Seal, Sir John Anderson (1882-1958). Over half a million Anderson Shelters were distributed between February 1939 and the start of the Second World War. By mid-1940, 2.5 million Anderson Shelters were provided (Jones, 2006). Anderson Structures were designed to be placed outside a family’s home, in their garden and accommodated a family of six (See Figure 1). Because they were made of corrugated iron and steel, they were ductile and inexpensive to produce.

![Figure 1: Photograph of a family entering an Anderson Shelter](image)

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1 The severity and frequency of bombing in the Second World War far surpassed that of the First World War. The death toll in London increased from 670 in WWI, to in the excess of 40,000 by May 1941 (Jones, 2006). After two years of bombing, by the end of 1941, more than 190,000 bombs were dropped on Great Britain; 44,000 civilians – including 5,500 children – were killed and 50,000 people were severely injured (Hicks, 2001).
Due to their ductility, which is a principal component in the achievement of plasticity (See Section 1.1.3.1 Fundamentals of Plastic Theory), the Anderson Shelters performed well under blast and ground shock. However, there were flaws in their design. The design of Anderson Shelters was based on the shelters used in the Spanish Civil War (Cowan, 1979) and the climate in Spain was more suitable for outdoor shelters than in Britain. Anderson Shelters were prone to flooding and did not protect occupants adequately from the harsh British winter (Jones, 2006).

After about a year of war, even in vulnerable areas, people were becoming reluctant to go night after night to a public shelter and they also tended to sleep in the house rather than go outside to a garden shelter. (Astbury, 1946).

Because of the discomfort British experienced while using Anderson Shelters, they were severely underutilized by the British population. Only 27% of British citizens used the Anderson Shelters according to the 1940 British census and many remained in their homes without additional protection or returned to crowded public shelters (Jones, 2006).

The known underutilization of Anderson Shelters made comfort and usability a key concern in the design of future air raid shelters. “It was soon realized that there was a factor other than structural safety essential in shelter design and that was ‘occupancy factor.’ It was impossible to claim that a shelter was efficient, however small its vulnerable area, if its occupancy factor was zero, that is to say if no one would use” (Baker, 1978).
1.1.2 The Indoor Shelter

The flaws (e.g., flooding, dampness, inconvenience and cold) in the other civilian shelter options, notably the Anderson Shelter, made the design of indoor shelters inevitable.

[The flooding in Anderson Shelters] was bad enough in early weeks, but the prospect of it continuing into the winter, when most of the shelters would be damp and may be flooded, was serious, threatening as it did the people’s health and sleep and so their efficiency. A shelter in the home was the only solution and so the problem was reviewed. (Baker, 1965)

The idea of an internal shelter had been often mooted particularly after it was found that outdoor shelters Andersons were uncomfortable places and in fact casualties were occurring because in spite of individual shelter provision people were flocking to public shelters for the sake of community life—a condition brought about principally because of the concentration on night bombing. (Webster, 1940)

Although it appears sensible in retrospect, indoor shelters were initially resisted by British officials. In December 1938, the Secretary of State for the Home Department presented Command Paper 5932 (Anderson, 1939), which considered “aspects of the Problem of Air Raid Shelters”, to Parliament by command of His Majesty (See Appendix B, Section II). Although the report acknowledges that, “the provision of a shelter in or in close proximity to the home of every citizen in vulnerable areas is a sound policy,” the report condemns the idea of putting shelters within homes: “With regard to the position to be occupied by these shelters we are definitely opposed to the placing of them within houses.” The report lists seven reasons why indoor shelters are not suitable. Notably, it argued that indoor shelters reduce the chance of rescue should there be an event that causes a home to collapse, and potentially would entrap occupants, with “the prospect of
a lingering death increased if the house collapses.” Although some of the concerns in Command Paper 5932 were valid and needed to be incorporated into the design of an indoor shelter, many of them were proven irrelevant by data collected from actual experience during the first few years of war. See Appendix C for full response to each of the concerns of Command Paper 5932 from January 1941.

In March of 1941, Professor John Baker introduced the Morrison Shelter as an alternative domestic shelter. The Morrison Shelter was an indoor shelter that served the dual purpose of a table and a bed (See Figure 2). It was composed of a frame made of steel angles with mesh surrounding the sides, to protect from splintering and to keep the occupants inside the shelter. It was designed to accommodate a family of two adults and two children. The structure was named after Herbert Morrison (1888-1965), who served as the British Minister of Home Secretary from 1940 to 1945.

Professor Baker designed the shelter using the newly developed plastic theory to absorb the energy of a collapsing house due to a near miss of a large bomb. The structure was an open frame with dimensions 6'-6" by 4' and 2'-6" tall (See Figure 3). This
framework facilitated easy escape so occupants could vacate or be rescued from all four directions in case one (or more) side(s) of the shelter became blocked, entrapping its occupants, which was a primary concern of Command Paper 5932.

Baker chronicled the difficulties of bureaucracy and production of the Morrison Shelter during the war in his book *Enterprise versus Bureaucracy* (Baker, 1978) (See Appendix F). Baker endeavored to make the shelter capable of mass-production while making certain that it remained lightweight and low-cost. Ultimately, 1,174,201 shelters
were produced at a manufacturing cost of £7.12.6\textsuperscript{2} (Freeman, 1950). The shelters were distributed for free to the families who would have received Anderson Shelters (ARP, 1939). The Morrison Shelter arrived as a kit with a pamphlet on how to erect it with simple images and directions – two people or a troop of volunteering boy scouts could assemble it in two hours (Baker, 1964).

1.1.3 Plastic Theory

1.1.3.1 Fundamentals of Plastic Theory

Conventional steel design employs elastic theory, which assumes idealized stress distributions that do not take full consideration of the ultimate strength of a material. Plastic theory, on the other hand, tries to understand the collapse behavior of steel for more efficient designs. As Jacques Heyman states:

The plastic designer makes a trivial inversion of the design statement: instead of requiring a building to stand up, he requires it not to fall down ... This collapse concept involves permanent plastic deformations rather than hypothetical elastic states ... plastic calculations gave a far more accurate representation of reality than elastic calculations. (Heyman, 1987)

The design of steel frames traditionally used the working stress method. This elastic method finds the point at which steel first fails, the yield stress (see $\sigma_0$ in Figure 4), and adds a safety factor so that each member is sized so that this stress is never exceeded within the structure (Baker, 1949). Thus, the maximum allowable stress method constrains the economy of steel structures.

\begin{footnotesize}
\textsuperscript{2} £7.12.6 is equivalent to $9.12$. With historical UK inflation is taken into account, a single Morrison Shelter cost £365.97 ($471) in 2017.
\end{footnotesize}
The carrying capacity of steel beyond the elastic range is due to steel's ductility and ability to distribute stress by "draw[ing] upon the reserve strength of its less heavily stressed portions" (Beedle, 1955). After reaching the yield point, steel continues to carry load in the plastic range.

When a fixed beam is loaded past elastic bending, locations of high stress become strained and experience permanent deformation. This deflection takes form in plastic hinge (See Figure 5c for locations of plastic hinges). The formation of plastic hinges allows regions of high stress to remain below the ultimate yield stress by carrying the full plastic moment, $M_p$ (Baker, 1949).
In Figure 5, \( M_y \) represents the elastic yield moment, which is achieved at the ends of the beam with a value of \( M_y = \frac{Wl}{12} \). While the plastic moment occurs at both the ends of the fixed beam and the midpoint with a value of \( M_p = \frac{Wl}{16} \). The moment required to resist the same load saves 25% of steel using plastic theory instead of the conventional elastic theory.

For collapse to occur in frames, the number of plastic hinges developed needs to cancel out the redundancies of the structure to make it determinant. Then the structure forms a collapse mechanism. Once a mechanism forms, the structure will continue to
deform under constant load (Symonds, 1951). In the case of a rigidly connected frame, four plastic hinges need to be formed. When these hinges exist in the structure a mechanism is formed. Three examples of mechanisms can be seen below in Figure 6. It is important to note that these pinned-frames are experiencing collapse due to vertical and horizontal concentrated point loads. The top frame fails due to sway collapse, the middle frame is a combination mechanism and the lowest frame is a beam failure. Figure 7 shows the same three mechanisms as in Figure 6, and highlights the internal rotation at the plastic hinges.

![Diagram of failure mechanisms](image)

**Figure 6:** Failure mechanisms of pinned-base frame under horizontal and vertical point loads (Baker, 1949)

**Figure 7:** Depiction of frame failure mechanisms with angular rotation
The motivation for the use of plastic theory in air raid shelters was the increased capability to absorb energy. As Baker recognized, “the energy which the beam absorbs before collapse is measured by the area under the load-deflexion curve” (Baker, 1948). See Figure 8 for comparison of elastic absorption versus plastic absorption. In order to achieve this greater energy absorption the structure needs to adhere to the assumptions of plasticity, which include ductility and continuity. Ductility is achieved via material selection and continuity is achieved by rigid connections. In designing air raid shelters, “the secret was to provide the structure with continuity and ductility, so that enormous amounts of energy could be absorbed without collapse or damage to the occupants” (Heyman, 1987).

![Stress vs Strain Curve](image)

**Figure 8: Stress vs Strain Curve from “Plastic Theory – It’s application to Design.”**
The triangle between O, A and the x-axis represents the energy absorbed by elastic theory. The area under the whole curve represents the plastically absorbed energy (Baker, 1941)

### 1.1.3.2 Development of Theory

Professor Baker was a key contributor to the adoption of plastic theory in England; in twelve years, Baker pushed the theory from an idea to a codified clause in the British Standard Specification No. 449 (BSS 449) (Heyman, 1987). Before the advent of the Second World War, from August 1929 to January 1937, Baker served as the technical
officer for the Steel Structures Research Committee (SSRC), in which he became
intimately aware of the limitations of the current steel codes that relied on elastic theory.
The SSRC sought “to review present methods and regulations for the design of steel
structures” and “to investigate the application of modern theory of structures” (SSRC,
1931). It assessed the contemporary global steel codes, performed its own experimental
tests on steel frames and published a revised method for the elastic design of steel frames
in its final report (Baker, 1949). However, by the SSRC’s final report in 1936 it was clear
to Baker “that the [elastic] method of design inherent in the (1939) Code of Practice was
almost entirely irrational and therefore incapable of refinement” (Morris, 1983).

In 1936, Baker recognized the need to move beyond elastic methods of design and
into the exploitation of plastic theory (Heyman, 1987). Following the SSRC, Baker along
with his then post-doctoral student, Professor Jack Roderick, performed extensive
experimentation on simple portal frames at the University of Bristol (Heyman, 1987). By
the outbreak of the Second World War, the power of plastic collapse had been proven,
however, the theorems proving it were still in development. Although the war slowed the
technical development, the war also necessitated efficient utilization of steel because “it
became of vital importance to conserve the national resources of steel” for the war effort
(Baker, 1954). In 1939, Baker reported to the British Steelwork Association with the
Recommendations on Higher Working Stresses in Steel Structures, in which he
recommends increasing the allowable stress in beams from 8 to 10 tons per square inch as
a result of his studies on the capacity of steel in the plastic range (Baker, 1954). By May
of 1940, this recommendation was temporarily codified as an amendment to the British
Standard Specification No. 449 titled “War Emergency Revision to BSS 449” (Baker,
1941). Ultimately, BSS 449 was permanently modified in 1948 to include a single clause permitting plastic design, based on “the results of an investigation into the behaviour of members carried out of the elastic into the plastic range” (Baker, 1954). Baker’s recommendation, however, relied solely on empirical tests from his labs without the fundamental plastic principles established (Heyman, 1987).

1.2 Research Motivation – Plasticity used in Morrison Shelter Design

The Morrison Shelters were undoubtedly important in saving civilian lives during WWII. Most publications on the structure focus on the lifesaving effects and the concerns with mass production. In his own recounting of designing the Morrison Shelter, Baker claims “it was comparatively easy to state the problem and to produce an initial design, the difficulties of supply and mass production in wartime were such that many amendments had to be made before final approved design could be issued” (Baker, 1948). Baker emphasizes the importance of actualizing production over the significance of the theory it executes.

Likewise, the publications on the Morrison Shelters tend to be geared towards the layman rather than focused on the calculations behind the structures. This thesis aims to uncover and verify the calculations Baker used to create the Morrison Shelter and better understand the significance of plasticity in the design process.

1.3 Research Objectives

This thesis seeks to review the significance of the Morrison Shelters, from the perspective of plastic theory. Since the Morrison Shelters were an early application of the theory the thesis will investigate the influence of plastic analysis on the design of the shelter. The objective of this thesis is to answer the following research questions:
1- Significance of Historical Design Requirements: What were the design criteria of
air raid shelters that made them suitable as an early application of plastic theory?

2- Technical Significance of Plastic Theory in the Design of the Morrison Shelter:
How was the Morrison Shelter calculated? What was the quantitative impact of
designing the Morrison Shelter using plastic theory?

3- Theoretical Significance of Morrison Shelters: How significant was the Morrison
Shelter in the history of plastic design of steel structures?
2 Literature Review

Many historians of structural engineering have acknowledged Professor Baker’s contributions to the development of plastic theory and have recognized that the Morrison Shelter was an important early application of plasticity (Heyman, 1987). Several years after the war, Professor Baker published accounts discussing some aspects of the design process of the shelter and its successful application during the war effort. These sources include Enterprise versus Bureaucracy (Baker, 1978) and a two volume series titled The Steel Skeleton (Baker, 1954 and Baker, 1965). Because Baker “set out to write an account of the steps taken in design, simple enough for a layman to appreciate” (Baker, 1978), his accounts discussed the general design process used in designing the Morrison Shelter, but he did not explicitly show the calculations that supported his design process. Likewise, the importance of plasticity in the design of the Morrison shelters is noted, but this claim is not supported quantitatively. There does not appear to be any publication that analyzed the calculations used by Professor Baker in the creation of the Morrison Shelter. The following section will touch on the subjects covered in these publications and the development of plastic theory relevant to this thesis’s research questions.

2.1 Technical Literature Review

Some of the most useful sources were published during the development of plastic theory are “Indoor Shelter” (Baker, 1948), Theory of Limit Design (Van den Broek, 1948), “A Review of Recent Investigations into the Behaviour of Steel Frames in the Plastic Range” (Baker, 1949), “The design of steel frames” (Baker, 1949), “Recent progress in the plastic methods of structural analysis” (Symonds, 1951) and the lecture notes from Beedle’s summer course at Lehigh University (Beedle, 1955). Sources that are

Some of the prominent contributors to the development and application of plastic theory include J.F. Baker, J.W. Roderick, M.R. Horne, B.G. Neal, W. Prager, P.S. Symonds and D.C. Drucker. An overview of the key publishings can be seen in Figure 9 - this list is directly from the lecture notes delivered by Beedle at Lehigh University the summer of 1955.

### 1.4 HISTORICAL NOTES

1914 : Kazinczy - Tests on indeterminate beams, concept of "yield hinge".

1917 : Kist - Design procedures utilizing ultimate load capacity.

1926 : Grünning - Difficulties with general loading (Shake-down problem).


1931 : Girkmann - Discusses Portal Frames.


1936 : Cambridge University, Prof. Baker and Colleagues.

1941 : Van den Broek
2.1.1 Historical Overview of Development of Plastic Theory

The work on the development of plastic theory can be divided into two parts: before and after World War II. The design of the Morrison Shelter, which employed plastic theory, occurred during the war, between these two phases of plastic theory development. The development from 1936 to 1939, largely took place at the University of Bristol with Professors Baker and Roderick (Baker, 1965). This thesis focuses on the application of the results of empirical studies of plastic deformation on steel frames from Bristol, as they directly relate to the performance of the Morrison Shelters.

2.1.2 Plasticity and the Expansion from Beams to Frames

From 1939-1945 the Institute of Welding conducted a number of tests on rigidly jointed portal frames (Baker, 1948). However, Karl Girkmann (1890-1959) had already performed experiments testing plastic theory related to the behavior of frames in 1931. Girkmann understood that the use of plastic theory in design could save weight, reduce maximum moment, and even out the differences in thickness of required cross-sections to simplify construction details and reduce cost (Kurrer, 2008). Without referencing Girkmann’s work, in 1949 Baker published similar empirical studies determining the bending moment distribution in steel frames at the plastic limit state.
Baker’s work was motivated by his own realization that elastic theory did not reflect the actual stresses experienced in structures and by the work of Hermann Maier-Leibnitz (1885-1962) on the plastic behavior of rigidly constrained beams. The summer of 1936 Baker met Professor Maier-Leibnitz, who was a significant contributor to the development of plastic theory on continuous steel beams at the 1936 International Association for Bridge and Structural Engineering conference in Berlin. Maier-Leibnitz “expressed confidence in the possibility of basing designs on plastic behaviour but, … stated that he had played his part in carrying out the tests on beams, and hoped that some younger man would undertake the larger task of producing a general design method” (Baker, 1965). Over the next twelve years, Baker picked up where Maier-Leibnitz left the work by bringing the idea of plastic theory “from an idea glimpsed in 1936 to an officially-permitted method in 1948” (Morris, 1983).

2.2 Review of the Literature on the Morrison Shelter Design Process

This thesis seeks to uncover the design decisions made by the “engineers and scientists” who created the Morrison Shelter. In Herbert Morrison’s autobiography, his reflection on the design process is focused on his own view from a manager’s perspective rather than the technical theories that were employed in the design of the shelter. He proudly states he that “decided on the principle and then forced the department’s engineers and scientists to produce a design within twenty-four hours by threatening to lock them up in a room until agreed” (Donoughue, 1973). Morrison’s interest in the design process remained political and focused on the government’s need to protect civilians rather than focused on the technical perspective from the department’s engineers and scientists. More details chronicling the design process are found in Appendix F.
Baker is the most reputable source addressing the technical design criteria considered in the design of the Morrison Shelter. Baker highlights the lack of published material on the technical developments:

Though from 1939 to 1945 air raid shelters were of great interest to most important people in Britain and were of importance in maintaining the morale of the civilian population, no complete account of their development is available. T.H. O’Brien in his volume of the History of the Second World War, Civil Defence, had such an enormous canvas to cover that he could not include technical detail (Baker, 1978).

Baker recounts the design process, from a technical viewpoint in *Enterprise versus Bureaucracy*, but his target audience is the layman, whom he wants “to appreciate something of the thrill and satisfaction of an engineer’s work” (Baker, 1978). He discusses the social impact but less so the technical requirements, i.e., loads supported by the shelter. This section will reveal the findings in the published materials on the design of the Morrison Shelter.

Baker states, “the first step in design is to define the problem, to state clearly the aim and object of the exercise, then to list any constraints and other difficulties that must be overcome” (Baker, 1978). He designed the Morrison Shelter with this approach. The problem was to create an indoor air raid shelter that minimized volume, weight, cost and material used. The seven constraints were predetermined by the Command Paper published by Anderson in 1938 (See Appendix B). Wartime experience made many of these concerns irrelevant (See the response to each concern in Appendix C). However, some of these concerns, especially the ease of exit which “is the most fundamental requirement of a proper shelter” (Baker, 1978), needed to be addressed in the shelter design.
All that the designer in 1940 had to do was to consider these seven objections and find ways of overcoming them. He had two powerful advantages over the panel working in 1938. He had the evidence of the full scale experiments being provided by the enemy and he was not constrained by the elastic theory of structures (Baker, 1978).

Additionally, the shelter needed to be easily assembled, so “this meant that the parts had to be dimensioned so that, wherever they came from they could be fitted together by unskilled labour, usually Boy Scout volunteers” (Baker, 1978).

The data collected after the 1938 Command Paper showed that damage from near misses caused the second floor of a house to fall in one piece onto the floor below, either vertically or hingeing about one wall -- the latter being a more critical load case (Baker, 1978). Thus, the shelter must be able to withstand the fall of a floor weighing 20psf from the story above -- typically 9 feet high (Baker, 1965).

Baker notes, “to absorb this energy elastically would of course have needed so much steel, about 2 ½ tons per shelter, as to make this project practically impracticable” (Baker, 1965). This claim is not supported by any calculation or design illustrating the dimensioning of an elastically designed shelter to check the validity of this assumed weight. Section 4.3 verifies Baker’s claim with elastic calculations.

Baker goes on to explain plastically absorbing the energy “was made practicable, however, by considering the shelter as a rigidly jointed portal with an allowable deformation of 12 in., the distance the top longitudinal angle could deflect without touching the occupants lying in the shelter” (Baker, 1965).
3 Methodology

This thesis seeks to uncover various aspects of the significance of plastic theory in the design of the Morrison Shelter; therefore, the methodology in its investigation is also multifaceted. First, the contemporary design criteria for air raid shelters are collected, then Baker’s calculations to size the Morrison Shelter’s frame are replicated, and the significance of the use of plastic theory is questioned by comparing the amount of steel used in a comparable table shelter design employing elastic theory. Lastly the Morrison Shelter is reviewed in the context of the development of plastic theory.

3.1 Review of criteria in designing the Morrison Shelter

Baker’s Enterprise versus Bureaucracy gave the most detailed, published description of the calculations involved in designing the Morrison Shelter. Because of the lack of published resources on the technical design of the shelter, the Baker Papers at Churchill Archive Centre were searched by the author for further technical material related to the Morrison Shelter design. Professor Baker saved 202 boxes pertaining to his life’s work at the archives; specifically 156 files within ‘Wartime work’ from 1925-1978 were examined to find relevant calculations to the Morrison Shelter. In addition to searching explicitly for calculations related to the Morrison Shelter design, the archives were investigated for data related to the contemporary criteria on designing air raid shelters and the user performance of the Morrison Shelter to understand the shelter’s success beyond its ability to deform plastically.

3.2 Technical Significance

To highlight the significance of using the burgeoning plastic theory in the design of the Morrison Shelter, first the calculations employed in design of the Morrison Shelter
were reviewed and then the steel savings were assessed by comparing it to a steel-framed shelter of the same global dimensions that were sized according to elastic theory.

### 3.2.1 Revisiting Calculations of the Morrison Shelter

The calculations of the Morrison Shelter were chronicled in confidential papers that were donated by Baker to the Churchill Archives Centre at Cambridge University. Some relevant papers have been reproduced as Appendices, notably Appendix E: “Design and Testing of the Table (Morrison) Indoor Shelter” (R.C. 204, 1941). These calculations have been reexamined for validity using plastic theory applied to frames experiencing vertical loading.

The Morrison Shelter calculations assume the impact of the entire floor above falls directly onto the shelter in an uniformly loaded fashion. Because the falling floor has no horizontal load, the failure mechanism assumed is beam failure (See Figure 6c), with three plastic hinges forming a mechanism. However, the mechanism differs from that in Figure 6 because the Morrison Shelter is continuous with rigid connections at both ends of the stanchion connections (it has a rigid base). Thus the uniform load on the frame needed to cause a mechanism is calculated in Eq. 3.1 by equating the external energy \( W_e \) and internal energy \( W_i \) absorbed by frame. The external work is equivalent to the uniformly distributed load, \( w_u \), times the length of the beam, \( l \), and the average deflection \( \delta_{avg} \). The internal work is defined by plastic moment of rotation, \( M_p \), times the angle of rotation, \( \theta \), at each plastic hinge (See Figure 7 for internal angle rotation of the beam failure mechanism). The \( \delta_{avg} \) is defined as \( \frac{\theta l}{4} \) for the uniformly loaded frame, to derive Eq. 3.2.
\[ W_e = W_i \quad \text{Eq. 3.1} \]

\[ w_a l \cdot \delta_{\text{avg}} = 4M_p\theta \]

\[ w_a l \frac{\theta l}{4} = 4M_p\theta \]

\[ w_a = \frac{16M_p}{l^2} \quad \text{Eq. 3.2} \]

Equation 3.2 is expanded to represent the absorbed energy of the frame by multiplying it by the maximum deflection:

\[ (w_a l)\delta = \left(\frac{16M_p}{l}\right)\delta \quad \text{Eq. 3.3} \]

\( M_p \) represents the plastic moment, which is defined as:

\[ M_p = Z\sigma \quad \text{Eq. 3.4} \]

Where \( Z \) is the plastic moment section modulus and \( \sigma \) is the strength of steel (Note: In Baker’s papers \( \sigma \) is denoted as \( f \)). Combining and rearranging Eq. 3.3 & Eq. 3.4 gives the simple formula equating absorbed energy from a global scale with the summation of the energy absorbed at each plastic hinge:

\[ \text{Absorbed energy} = \frac{16fZ\delta}{l} \quad \text{Eq. 3.5} \]

The key in achieving this absorbed energy is continuity and rigid connections. Baker comments that the steel rolled angles are rigidly jointed by bolts through gusset plates (Baker, 1965). Since the absorbed energy of the falling floor can be estimated, sizing the frame elements is done by solving for \( Z \) (See Section 4.2).

---

3 Baker’s notation uses \( f \) for yield stress instead of \( \sigma \)
3.2.2 Comparing Elastic versus Plastic Design of the Morrison Shelter

The first step in assessing the impact of plasticity on the efficiency of the Morrison Shelter is calculating the weight of the actual shelter design. Baker states, even after accounting for additional weight due to mass production, the Morrison Shelter weighed 5cwt (Baker, 1965), which is 560 pounds. This claim is verified by both a page found in the archives labeling the weights of the parts within the Morrison Shelter (See Appendix H) and with calculations done for this study (See Table 1 in Section 4.3).

The second task is to size the shelter using elastic theory and the same global dimensions as the original Morrison Shelters. The elastic section modulus, S, was used to size the frame elements. The elastic equivalent to Eq. 3.4 was used:

\[ M_p = S\sigma \]  

Eq. 3.6

The results of sizing a comparable shelter using elastic theory can be seen in Table 2 in Section 4.3.

Finally, the weights of the structural elements (i.e. the angles acting as the frame and disregarding the grillage, connection elements and the top plate, which are assumed to remain constant between plastic and elastic designs) are compared to show the material savings.

3.3 Technical Development

To understand the role the Morrison Shelters played in the development of plastic theory, the maturity of the theory needs to be understood both before and after the design of the Morrison Shelter. The following sources were consulted to understand the development of the plastic theory: Baker (1948), Van den Broek (1948), Symonds (1951), Pippard (1968), Cowan (1979), Morris (1983), Heyman (1998), Kurrer (2008),
and Stein (2014). The goal of this research objective is to understand the context in which the Morrison Shelter was created, so that the Morrison Shelter’s influence can be understood.
4 Results

4.1 Review of Design Criteria for Morrison Shelter

The success of the Morrison Shelter depended on how it could perform under the collapse loads and how it addressed the comfort of the user. The initial design criteria of the Morrison Shelter were created as a response to the Command Paper 5932 (See Appendices B). Some of the suggestions from Command Paper 5932 were incorporated, such as serving a two-story house that accommodates at least four people, and keeping the weight of any steel element under 100 lbs. Other design criteria were in direct opposition to the concerns of Command Paper 5932 (See Appendix C) – for this reason a flat-topped shelter with dual purpose as furniture and an open framework to minimize occupant entrapment were used.

The most critical quantitative design criteria for the performance of the shelter are the expected loads on the shelter. In searching through the Baker Papers at the Churchill Archives, the following was found on the design load requirements.

According to the “Shelter for Use Indoors” report published by the Ministry of Home Security Research and Experiments Department on December 17th, 1940 the following debris loads must be supported by a proposed air raid shelter design (See Appendix D for copy of original document):

(i) 320 psf static load over the whole area of the shelter
(ii) The weight of the area of the floor 14 ft x 6 ft-6in by 20 psf falling flat on the shelter from a height of 8 feet
(iii) The same floor load as described in (ii) hinged about one wall and striking the shelter obliquely
(iv) 160 psf static load applied to any side of the shelter
Additionally, the "Merseyside" correspondence from Baker on February 1st, 1941, outlines the required static loads to simulate the impact loads expected from the floor falling onto the shelter (See original document in Appendix J):

The load to which an indoor shelter is liable to be subjected is, of course, uncertain. Experience of a large number of cases of damage to domestic dwellings has, however, led us to the conclusion that the most probable eventuality is the demolition of one or more walls of a room, leading to the collapse in one piece of the 1st floor. This floor will then hinge down about a surviving wall and strike the shelter obliquely. We have done a number of tests on various indoor shelters struck in this way by a falling floor and it appears that, if the shelter is to withstand this impact loading, it should be designed for a vertical load of about 200 lb. per sq. ft. and a horizontal load of about 100 lb. per sq.ft.. (Baker, 1941)

From these two documents it can be assumed that the impact load of the falling first floor onto the lower floor can be simulated using static loads. To compare the impact of using the plastic theory in the design process, these static loads can be used to size a comparable shelter using elastic theory (these results can be found in section 4.3).

4.2 Review of Baker’s Plastic Calculations for Morrison Shelter Members

The purpose of this section is to review Baker’s plastic calculations used to design the Morrison Shelter. The steps of these calculations are laid out in the confidential paper titled *The Design and Testing of the Table (Morrison) Indoor Shelter* (R.C. 204, 1941). The original document that was found in the Churchill Archives Centre has been reproduced in Appendix E.

The first step in sizing the Morrison Shelter is to determine the shelter’s dimensions and to approximate the magnitude of the load falling on it. To support its secondary uses as a dining room table and as a bed, the global dimensions of the shelter
were predetermined. It has a height of \(2'-6''\) for the appropriate table height, with a length of \(6'-6''\) and a width of \(4'-0''\) that are the typical dimensions of a mattress. It was decided that the shelter could deform twelve inches vertically without impeding too much on the occupants. As discussed earlier, the critical load case is assumed to be the second floor falling onto the shelter, by swinging down and rotating from one wall. The greatest dimension of a standard room is estimated at fourteen feet. The weight of the floor is approximated at 20 psf (20 psf is derived from 16psf for one inch tongued and grooved boards on 9”x2” joists at 14” centers, with a lath and plaster ceiling and 360 lbs of furniture above the shelter).

To size the frame members the amount of energy absorbed needed to be defined. The typical story height is \(8'-6''\), for these calculations it is assumed to be nine feet tall. The potential energy is defined by the simple calculation of \(PE=mgh\). The weight of the floor falling on the shelter is \(20\text{ psf} \times 14' \times 6.5' = 1820\text{ lbs}\) and the distance of the falling floor to the top of the shelter is \(6'-6''\). Thus the shelter must be able to absorb 11,830 lb-ft (141,960 lb.-in.), which is approximated as 142,000 lb.-in. Baker estimates that half of this energy\(^4\) is absorbed by the shelter via plastic hinge formation.

To size the top rail of the Morrison Shelter along the long edge, according to the plastic deformation, Baker used the following equation, which is derived from the beam-failure mechanism in plastic frame analysis (See derivation in Section 3.2.1):

\[
\text{Absorbed energy} = E = \frac{16 JZ\delta}{l}\tag{3.5}
\]

\(^4\)“Only tests could show how much of this energy is communicated to the shelter and how much is absorbed by the floor itself. For the purpose of a rough preliminary design (to be checked by subsequent tests) it was assumed that one half was absorbed by the shelter” (RC 204, 1941)
Equation 3.5 is rearranged to solve for the plastic modulus, since the amount of absorbed energy is known:

\[ Z = \frac{EI}{16f\delta} \quad \text{Eq. 4.1} \]

Because the Morrison Shelter consists of two frames in parallel and only half of the energy of the collapsing floor is attributed to the shelter, the total energy needed to be absorbed by each frame is \( \frac{142,000}{4} = 35,500 \text{ lb-in} \). The other variable values used are as follows:

\[ f = \text{effective yield stress of material} = 18 \text{ tons/in}^2 = 36,000 \text{ lb/in}^2 \]
\[ Z = \text{plastic modulus} \]
\[ \delta = \text{deflection of top rail} = 12'' \]
\[ l = \text{span of top rail} = 6'-6'' = 78'' \]

In Baker’s report he writes that the plastic modulus section required is 0.35 in\(^3\), however in replication of these calculations it appears that the required section is actually 0.40 in\(^3\):

\[ Z = \frac{EI}{16f\delta} = \frac{(35,500 \text{ lb-in})(78'')}{16 \cdot (36,000 \text{ lb/in}^2) \cdot 12''} = 0.4 \text{ in}^3 \quad \text{Eq. 4.2} \]

This difference in plastic modulus becomes irrelevant because the chosen angle of 3”x2.5”x1/4” has a higher section modulus of 1.00 in\(^3\) (AISC, 2005). If this actual plastic modulus is substituted back into the following equation:

\[ \delta = \frac{EI}{16fZ} = \frac{(35,500 \text{ lb-in})(78'')}{16 \cdot (36,000 \text{ lb/in}^2) \cdot (1.0 \text{ in}^3)} = 4.8'' \quad \text{Eq. 4.3} \]

the expected deflection (with the same energy absorption assumptions) is 4.8 inches.
A physical study confirms the validity of these calculations. The set up can be seen in Appendix I. For this study the 3"x2"x0.25" angle was tested. This angle, reportedly, has a plastic section modulus of 0.52 in$^3$ (R.C. 204, 1941). Using this 0.52 as the Z value, the expected maximum deflection of this angle is:

$$\delta = \frac{EI}{16fZ} = \frac{(35,500 \text{lb-in})(78\text{''})}{16\left(36,000 \text{lb/} \text{in}^2\right)(0.52 \text{in}^3)} = 9.24\text{''}$$

Eq. 4.4

The maximum deflection from this test on the 3"x2"x1/4" angle is reported as 6.25 inches. This physical study confirms the validity of these calculations. The expected value of 9.2" exceeds the actual deflection the shelter by 27%. The actual performance is due to the fact that these calculations assume the steel angle is the only contributor to the plastic section modulus, however, the $\frac{3}{8}\text{''}$ steel top plate also contributes to the built up plastic section modulus in the Morrison Shelter. This additional steel element, which is rigidly connected, provides increased moment capacity of the shelter allowing it to absorb more energy plastically.

4.3 Comparing Steel Weights of Designs using Plastic and Elastic Theory

The novelty of the Morrison Shelter is that it was designed using the developing plastic theory before it was fully realized. The advantage of using plastic theory instead of the conventional elastic theory is expressed in material savings. The final Morrison Shelter design weighed 448 pounds (See Table 1). For the purpose of this study only the outer frame is analyzed. Additional weight of the mesh coverings, steel laths and fixings for the mattresses and the nuts and bolts were not accounted for in these calculations.

---

5 Ultimately, due to limited availability of steel angle supply this angle was not chosen. It is assumed in plastic calculations that larger angles, with higher Z sections perform better.
because they were not calculated using plastic theory and thus do not influence material savings due to designing with plasticity.

The weight of the shelter using plastic theory is calculated in Table 1 below. The dimensions, length of elements and reported weight are all based on the findings in the Churchill archives, which has been reproduced in Appendix H. The calculated weight is comparable to the reported weight in the archived document.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uprights or legs</td>
<td>4</td>
<td>6&quot; x 6&quot; x 3/8&quot;</td>
<td>2'-5&quot;</td>
<td>14.9</td>
<td>144.0</td>
<td>148</td>
</tr>
<tr>
<td>Top side rails</td>
<td>2</td>
<td>3&quot; x 2.5&quot; x 1/4&quot;</td>
<td>6'-4&quot;</td>
<td>4.5</td>
<td>57.0</td>
<td>58</td>
</tr>
<tr>
<td>Bottom side rails</td>
<td>2</td>
<td>2.5&quot; x 2.5&quot; x 1/4&quot;</td>
<td>6'-4&quot;</td>
<td>4.1</td>
<td>115.8</td>
<td>112</td>
</tr>
<tr>
<td>Top end rails</td>
<td>2</td>
<td>2.5&quot; x 2.5&quot; x 1/4&quot;</td>
<td>3'-10.75&quot;</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom end rails</td>
<td>2</td>
<td>2.5&quot; x 2.5&quot; x 1/4&quot;</td>
<td>3'-10.75&quot;</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top of shelter</td>
<td>1</td>
<td>1/8&quot; thick</td>
<td>6'-5&quot; x 3'-11.75&quot;</td>
<td>5.1</td>
<td>130.2</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total weight (plastic method, uniform load)</strong></td>
<td><strong>447.1</strong></td>
</tr>
</tbody>
</table>

To compare the material savings due to the use of plastic theory, the same-dimensioned shelter is sized using elastic theory. From the results of Section 4.1, which determined the load requirements for air raid shelters, the use of 320 psf as a static load on the shelter is justified by the 1940 “Shelter for Use Indoors” report. Using the dimensions of the 1/8" thick steel top (6'-5" x 3'-11.75"), the static vertical load that needs to be supported by the shelter is 8,200 lb.

The following is a sample calculation of sizing the top-side rail angle using elastic theory of working stress method (mentioned previously in section 1.1.3.1). Since the Morrison Shelter features two portal frames in parallel, half of the tributary area is distributed to each side, thus only 4,100 lb is distributed on a single bay. The distributed load is \( w = \frac{4100}{6'-5"} = 53.25 \text{ lb/in} \), causing a maximum moment at the midpoint of the frame.
of $M_{\text{max}} = 38,950$ lb-in. Because the Morrison Shelter was designed after Baker's recommendation in 1939\footnote{The Morrison Shelters were designed in 1940 after Baker's 1939 "Recommendation on Higher Working Stresses in Steel Structures" advised increasing permissible stress from 8 to 10 tons per sq.in. (Baker, 1954).}, it is assumed that the allowable stress is 10 tons per square inch. The maximum moment and the allowable stress are inserted into the following equation, where $S$ is the elastic section modulus and $f$ is the maximum allowable stress:

$$M_y = Sf \quad \text{Eq. 3.6}$$

$$S_{\text{req}} = \frac{M_y}{f} = \frac{38,950\text{lb-in}}{20\text{ksi}} = 1.95\text{in}^3 \quad \text{Eq. 4.5}$$

The lightest angle that had an elastic section modulus that exceeded 1.95 in$^3$ was 5” x 3” x 3/8”. This angle had an elastic section modulus of 2.24 in$^3$ and weighs 9.8 pounds per linear foot. The same process was used to size the top end rail. The rest of the sizes were assumed to remain constant between the plastic and elastic sizings.

Table 2: Weight of Shelter -- Elastic Calculation with Uniform Load

<table>
<thead>
<tr>
<th>List of Parts</th>
<th>#</th>
<th>Dimensions [in]</th>
<th>Length [ft]</th>
<th>plf</th>
<th>Weight [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uprights or legs</td>
<td>4</td>
<td>6&quot; x 6&quot; x 3/8&quot;</td>
<td>2'-5&quot;</td>
<td>14.9</td>
<td>148</td>
</tr>
<tr>
<td>Top side rails</td>
<td>2</td>
<td>5&quot; x 3&quot; x 3/8&quot;</td>
<td>6'-4&quot;</td>
<td>9.8</td>
<td>124.1</td>
</tr>
<tr>
<td>Bottom side rails</td>
<td>2</td>
<td>2.5&quot; x 2.5&quot; x 1/4&quot;</td>
<td>6'-4&quot;</td>
<td>4.1</td>
<td>51.9</td>
</tr>
<tr>
<td>Top end rails</td>
<td>2</td>
<td>5&quot; x 3&quot; x 1/4&quot;</td>
<td>3'-10.75&quot;</td>
<td>6.6</td>
<td>51.4</td>
</tr>
<tr>
<td>Bottom end rails</td>
<td>2</td>
<td>2.5&quot; x 2.5&quot; x 1/4&quot;</td>
<td>3'-10.75&quot;</td>
<td>4.1</td>
<td>31.9</td>
</tr>
<tr>
<td>Top of shelter</td>
<td>1</td>
<td>1/8&quot; thick</td>
<td>6'-5&quot; x 3'-11.75&quot;</td>
<td>5.1</td>
<td>130.2</td>
</tr>
</tbody>
</table>

**Total Weight (elastic method, uniform load)** 533.7

Although Baker assumed uniform loading in his plastic calculations, to simulate the worst-case scenario of the second floor rotating about one wall and striking the shelter, a concentrated load case is calculated. It is assumed that the floor strikes the center of the shelter for the worst-case scenario with half of the floor still supported by
the wall, which it is rotating about. The following equations express the energy absorbed plastically with a point load at the center of the long side of the frame. They differ from Baker’s plastic calculations in that the \( W_e \) is \( \frac{Wl\theta}{2} \) instead of \( W_e = \frac{W_i^2\theta}{4} \) as expressed in Equation 3.2.

\[
W_e = W_i \quad \text{Eq. 3.1}
\]
\[
\frac{Wl\theta}{2} = 4M_p\theta \quad \text{Eq. 4.6}
\]
\[
W = \frac{8M_p}{l}
\]
\[
E = W\delta = \frac{8fZ\delta}{l}
\]
\[
Z = \frac{El}{8f\delta}
\]

\[
Z = \frac{El}{8f\delta} = \frac{(35,500\text{lb-in})(78'')}{8(36,000\text{lb/}	ext{in}^2)(12'')} = 0.8
\quad \text{Eq. 4.7}
\]

<table>
<thead>
<tr>
<th>List of Parts</th>
<th>#</th>
<th>Dimensions [in]</th>
<th>Length [ft]</th>
<th>plf</th>
<th>Weight [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uprights or legs</td>
<td>4</td>
<td>6” x 6” x 3/8”</td>
<td>2'-5”</td>
<td>14.9</td>
<td>144</td>
</tr>
<tr>
<td>Top side rails</td>
<td>2</td>
<td>3” x 2” x 1/4”</td>
<td>6'-4”</td>
<td>4.1</td>
<td>51.9</td>
</tr>
<tr>
<td>Bottom side rails</td>
<td>2</td>
<td>2.5” x 2.5” x 1/4”</td>
<td>6’-4”</td>
<td>4.1</td>
<td>51.9</td>
</tr>
<tr>
<td>Top end rails</td>
<td>2</td>
<td>2.5” x 2” x 1/4”</td>
<td>3’-10.75”</td>
<td>2.75</td>
<td>21.4</td>
</tr>
<tr>
<td>Bottom end rails</td>
<td>2</td>
<td>2.5” x 2.5” x 1/4”</td>
<td>3’-10.75”</td>
<td>4.1</td>
<td>31.9</td>
</tr>
<tr>
<td>Top of shelter</td>
<td>1</td>
<td>1/8” thick</td>
<td>6’-5” x 3’-11.75”</td>
<td>5.1</td>
<td>130</td>
</tr>
</tbody>
</table>

**Total Weight (plastic method, concentrated load)** 431.3

Table 4 illustrates the weight of the parts involved in an elastically calculated frame that is hit with a concentrated load. The same elastic working stress method was used as described in the creation of Table 2 for a uniform, elastically calculated shelter.
Table 4: Weight of Shelter -- Elastic Calculation with Concentrated Load

<table>
<thead>
<tr>
<th>List of Parts</th>
<th>#</th>
<th>Dimensions [in]</th>
<th>Length [ft]</th>
<th>plf</th>
<th>Weight [lb]</th>
</tr>
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<tbody>
<tr>
<td>Uprights or legs</td>
<td>4</td>
<td>6&quot; x 6&quot; x 3/8&quot;</td>
<td>2’-5”</td>
<td>14.9</td>
<td>144</td>
</tr>
<tr>
<td>Top side rails</td>
<td>2</td>
<td>5&quot; x 3&quot; x 3/8&quot;</td>
<td>6’-4”</td>
<td>9.8</td>
<td>124</td>
</tr>
<tr>
<td>Bottom side rails</td>
<td>2</td>
<td>2 1/2” x 2 1/2” x 1/4”</td>
<td>6’-4”</td>
<td>4.1</td>
<td>51.9</td>
</tr>
<tr>
<td>Top end rails</td>
<td>2</td>
<td>3” x 2 1/2” x 1/4”</td>
<td>3'-10.75”</td>
<td>6.6</td>
<td>51.4</td>
</tr>
<tr>
<td>Bottom end rails</td>
<td>2</td>
<td>5” x 3” x 1/4”</td>
<td>3’-10.75”</td>
<td>4.1</td>
<td>31.9</td>
</tr>
<tr>
<td>Top of shelter</td>
<td>1</td>
<td>1/8” thick</td>
<td>6’-5” x 3’-11.75”</td>
<td>5.1</td>
<td>130.2</td>
</tr>
</tbody>
</table>

**Total Weight (elastic method, concentrated load)** 533.5

Summary of results comparing elastic to plastic total steel weight:

<table>
<thead>
<tr>
<th>Calculation method, load case</th>
<th>Total [lb]</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic, uniform</td>
<td>447.1</td>
<td>-</td>
</tr>
<tr>
<td>Elastic, uniform</td>
<td>533.7</td>
<td>16%</td>
</tr>
<tr>
<td>Plastic, concentrated</td>
<td>431.3</td>
<td>-</td>
</tr>
<tr>
<td>Elastic, concentrated</td>
<td>533.5</td>
<td>19%</td>
</tr>
</tbody>
</table>

4.4 Theoretical Significance of Morrison Shelters

To determine the significance of the Morrison Shelters in the development of the plastic theory, it is imperative to understand the context in which it was created. Thus, this section will explain the development of the theory in relation to the design of the Morrison Shelter.

4.4.1 Plastic Theory Development Before the Morrison Shelter (1940)

The inception of plastic theory is hard to determine, it extends as far back to Galileo’s testing in 1683 and Mariotte’s work in 1686 (Morris, 1983). Despite Galileo and Marioette’s early musings, “Engineers,” as Baker notes in *Plasticity as a Factor of*...
"Design in War-time Structures, “have been strangely incurious of the real strength of modern building structures, confining their attention to the main conditions in the working range” (Baker, 1948). This is probably due to the influence of Navier (1785-1836) in formulating the elastic theory in 1826 (Morris, 1983). Navier’s method focused engineers focus on the prevention of collapse to ensure safety of a structure. Because of elastic theory’s simplicity it dominated structural design and acted as a “straight jacket” inhibiting the exploration of other theories (Heyman, 1998).


Closely related to plasticity is the concept of limit design. In 1907, C.M. Goodrich designed two towers for the hydro-electric power commission of Ontario using limit design (Symonds, 1951). Similarly as in plastic theory, the design of transmission tower (See Figure 10) depended on the ductile behavior of the steel trusses. Goodrich’s design was condemned and the weaker tower was torn down in 1910. The structure reportedly carried a fifty percent overload (Van den Broek, 1948). These structures were not well known and did were not influential in the development of plastic theory in Europe, and were likely not considered in the design of the Morrison Shelter. These transmission towers could be considered the first application of plastic theory, predating the Morrison shelters by three decades.
The catalyst behind the development of plastic theory in the twentieth century was Gábor von Kazinczy (1889-1964), the Hungarian who, in 1914, studied steel I-beams with fixed-ends encased in concrete (See Figure 11)(Kurrer, 2008). The concrete visually showed the hinging mechanisms that formed at the ends that were necessary for collapse (Heyman, 1998). Kazinczy found the maximum bending moment of the beam was WL/16, unlike the predicted WL/12 from elastic theory. The plastic theory, in this case, allowed for 25% of material savings (Cowan, 1979).
In 1928, Hermann Maier-Leibnitz reported on the true load-carrying capacity of a simply supported and continuous beam. He found the critical design moment occurred at the mid-span, with a magnitude of 75% of the support moment (Kurrer, 2003).

The Steel Structures Research Committee (SSRC), established in 1929 by a collaboration between the British Steelwork Association and the Department of Scientific and Industrial Research, sought to find more efficient ways to design with steel and “allow full advantage to be taken of the excellent qualities which steel possess as a material for building construction” (Pippard, 1968). John Fleetwood Baker, the eventual designer of the Morrison Shelter, was appointed as Technical Officer of the SSRC. The committee produced three volumes of findings. The last report, published in 1936, included *Recommendations for Design*. This code of practice was used to update British Standard 449 in 1936 (Pippard, 1968). Baker recognized that these recommendations

Figure 11: From Kazinczy's paper published in 1914 on fixed-ends steel beams
relied on conventional elastic theory and the most efficient design would utilize postelastic behavior (Cowan, 1979).

While the Baker was working with the SSRC in England, in 1931 at Vienna University of Technology, Karl Girkmann (1890-1959) performed the first collapse tests on portal frames that are reported in literature (Heyman, 1998). The pin-based frame with a point load collapsed after the formation of three hinges in the beam as a mechanism.

In 1932 the first congress of International Association for Bridge and Structural Engineering (IABSE) took place. After this first congress, the interest in plastic theory increased substantially. By the Second IABSE Congress in 1936, eight papers in the field of plasticity were presented (Heyman, 1998). The notable presenters from this congress include Maier-Leibnitz, Frederich Bleich (1878-1950) and Ernst Melan (1890-1963). Maier-Leibnitz reported on his numerous tests on continuous beams.

As discussed in Section 2.1.2, Professor Baker was inspired by the work of Maier-Leibnitz presented at the 1936 conference. Baker dedicated his research to the expansion of the plastic theory to incorporate the design of steel frames (even though these studies had already been performed by Girkmann in 1931). In 1936, along with J.W. Roderick, Baker studied the collapse of steel frames (Morris, 1983) and published “The Rational Design of Steel Building Frames” in June 1936 (Baker, 1936). Baker and Roderick refined their research and published “Investigations into the Behaviour of Welded Frame Structures” in the Trans Inst. Welding twice; first in 1938 and again in 1940 (Baker, 1948). In this publication they determined the deflection of overstrained beam has a drop of stress at yield based on the assumptions of plastic theory.
4.4.2 Influence of the Morrison Shelter on the development of plasticity

Baker was fully immersed in the development of steel plasticity when he was presented with the design task of creating the Morrison Shelters. Baker passionately believed in applying theory to physical testing and the Morrison Shelter provided the opportunity to apply the plastic theory beyond laboratory tests to mass-produced shelters. Also in 1941, after the design of the Morrison Shelter, Baker with Roderick published “Plastic theory—its application to design.”

Although the Morrison shelters proved successful, the application of plastic theory could not immediately be adopted into standard building practice after the end of the war, because the theory was not yet incorporated into the building code. Baker pushed for the addition of the theory to the British Standard 449. In 1948, BS 449 included a clause permitting the use of plastic methods (Kurrer, 2008). However, no guidance was given as to how the plastic method should be applied (Morris, 1983).

Baker continued to advocate for the theory to be incorporated into the engineering curriculum so young engineers would be aware of the power of the plastic theory and could apply it to future designs. Following the 1948 amendment to BS 449, Baker and his team at Cambridge University, encouraged British designers to use plastic theory by performing the plastic calculations for early applications; three of these early applications include the three new buildings of the Cambridge Engineering Laboratories (Heyman, 1987). One of which was the “Baker Building” (See Figure 12), which was built in 1952.
In reference to the application of plastic theory in the design of Cambridge University's Steel Building Research Center, Baker wrote:

[We had] the fun of designing the steel frame ourselves, trying out each time a more sophisticated method as it was developed by our structural research team. (Ahmed, 2017)

This Cambridge research team, which Baker refers to, was led by Michael Horne and Jacques Heyman who continued developing the plastic theory of design. They claim that by using plastic theory in the design of this research center, twenty percent of the steel was saved because of the reduction of structural beam depths from 20 inches, which is prescribed by elastic theory, to 14 inches (Ahmed, 2017). This acknowledgment of the savings due to the use of plastic theory is similar to the purpose of this thesis in recognizing the steel saved via plastic theory in the Morrison Shelters.

Even though plasticity was included in the building code in 1948, the principles behind the theory were still not fully understood by British designers (although it had previously been discovered by the Russian Professor A.A. Gvodev in 1938, but lack of distribution limited the spread of these principles globally). Because of the lack of
supporting principles to check the designs, “each structure, or structural type, was tackled \textit{sui generis}” (Heyman, 1987).

To expedite the development of plastic theory, cooperation between Cambridge and Brown Universities was developed via an exchange between Baker’s experimental lab and Professor William Prager’s team that worked on the principles of plastic theory.
5  Discussion

This section discusses the success of the work of this thesis relative to the research objectives that were introduced in Section 1.3:

1- Significance of Historical Design Requirements: What were the design criteria of air raid shelters that made them suitable as an early application of plastic theory?

2- Technical Significance of Plastic Theory in the Design of the Morrison Shelter: How was the Morrison Shelter calculated? What was the quantitative impact of designing the Morrison Shelter using plastic theory?

3- Theoretical Significance of Morrison Shelters: How significant was the Morrison Shelter in the history of plastic design of steel structures?

Each of these research questions will be evaluated in the discussion sections below.

5.1 Historical Design Requirements Significance

The notable findings from Section 4.1 on the requirements of the air raid shelter in relation to the application of plastic theory are found below in Table 6. These values can be used in further analysis to compare the plastically designed Morrison Shelter with elastically designed shelters that upheld these load design criteria.

<table>
<thead>
<tr>
<th>Table 6: Load Cases Requirements for Air Raid Shelters Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1940 “Shelter Use Indoors”</strong></td>
</tr>
<tr>
<td>a) 320 psf static load</td>
</tr>
<tr>
<td>b) first floor falls flat on shelter</td>
</tr>
<tr>
<td>c) first floor rotates about wall and falls obliquely onto shelter</td>
</tr>
<tr>
<td>d) 160 psf horizontal load</td>
</tr>
</tbody>
</table>
The inclusion of both the load requirements from the 1940 publication (Appendix D) and the letter from Baker in 1941 regarding the “Merseyside” shelter (Appendix J) may seem redundant, however it shows the refinement of the understood performance due to the collected data and empirical studies conducted during the war. Additionally, the 1940 data, although older, is from a more official source (the publication of the Ministry of Home Security’s Research and Experiments Department), while the 1941 letter was found in the Baker Papers in the Churchill Archive Center, its signature from J.F. Baker gives it credibility.

Additionally, the significance in studying the design requirements of the 1940s air raid shelters is to emphasize how the steel-frame geometry was suitable to assuage all concerns that were initially expressed in response to putting an air raid shelter indoors. Conveniently, the steel-frame was the natural progression of form in the development of plastic theory and was able allow for maximum ventilation, minimized occupant entrapment, and easy assembly due to simplicity of form and lightness. Due to its convenience for users, the framed geometry increased the likelihood of occupancy, making it a suitable early application of the plastic theory.

5.2 Technical Significance

The primary contribution of this thesis is its analysis of the technical significance of the Morrison Shelters. The technical investigation is divided into two components 1) the replication of the Morrison Shelter calculations and 2) the comparison of elastic and plastic designs.
5.2.1 Replication of Morrison Shelter calculations

Publications recall that the Morrison Shelter employ the plastic theory, and specifically *Enterprise versus Bureaucracy*, but they lack the technical rigor that is useful to see to apply it to future applications. Section 4.2 verifies the use of plastic method in the design of the Morrison Shelter.

Also, as seen from the expected deflection compared to the actual deflection reported from physical testing, the Morrison Shelter over performed (See Section 4.2, Eq. 4.4), due to increased capacity due to the attachment of the angles to the steel top plate. This performance ensured safety while still economizing the use of steel as compared to an elastically designed shelter. Further work can be done to demonstrate and quantify the increased capacity of the Morrison Shelter due to the rigidly connected top plate.

5.2.2 Comparison of Elastic and Plastic Designs

The most intriguing part of this thesis is section 4.3, which compares the elastic design of the Morrison Shelter with the actual design using plastic theory. This section studied elastic and plastic designs under uniform load, which was the load case Baker used in his calculations for the Morrison Shelter, and under a concentrated load. This second load case was studied, because as found in the section 4.1, the worst load case scenario is when the first floor hinges about one standing wall, to obliquely hit the shelter. This concentrated load represents the floor hitting the Morrison Shelter at one point instead of in a flat, uniform manner.

Table 5 summarizes the total findings of this section. However, to highlight the significance of plastic theory on the design of the shelter, only the weight of the structural
elements (those that were sized according to plastic theory) should be reviewed – this
analysis is represented Table 7 below:

Table 7: Weight of Structural Elements Comparison

<table>
<thead>
<tr>
<th></th>
<th>Side rails</th>
<th>End rails</th>
<th>Total</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic uniform</td>
<td>57</td>
<td>51.9</td>
<td>108.9</td>
<td></td>
</tr>
<tr>
<td>Elastic uniform</td>
<td>124.1</td>
<td>51.4</td>
<td>175.5</td>
<td>38%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Side rails</th>
<th>End rails</th>
<th>Total</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic point</td>
<td>51.9</td>
<td>21.4</td>
<td>73.3</td>
<td></td>
</tr>
<tr>
<td>Elastic point</td>
<td>124</td>
<td>51.4</td>
<td>175.4</td>
<td>58%</td>
</tr>
</tbody>
</table>

Previously, Baker had performed studies emphasizing the significance of plastic
theory instead of the conventional elastic theory on the amount of steel savings in frame
structures. Baker’s results are displayed below in Figure 13. The elastic method displayed
was based on the requirements according to the British Standard Specification No. 449
(the April 1932 edition). Baker found that plastic frames are “not unnaturally, appreciably
lighter than the elastic, and similar information for other portals shows that the
percentage difference increases with the height of the stanchion” (Baker, 1949).
Baker's findings align with the findings of this thesis, in that approximately 20% savings can be made by designing plastic frames instead of elastic ones. This thesis, unlike Baker's report looks at frames that have uniform load as well as the need to actually be produced and cannot be fully customizable as is possible in a laboratory set up.

5.3 Theoretical Significance

The need for economic steel designs during wartime inspired designers to expand their traditional methods to include more daring, but more efficient designs. Baker notes:

The possibilities of plastic deformations have been brought home very forcibly to many engineers in the past twelve months as a result of bomb damage to the structures for which they are responsible. A knowledge of the theory discussed in this paper made it possible to foretell with some accuracy the type of damage which a structure might suffer due to air attack. (Baker, 1941)
By pioneering the application of the plastic theory, steel was able to be used more efficiently and steel designers were liberated from the constraints of elastic theory that rely on safety factors and idealized geometries.

By 1955, over 175 industrial frames were reportedly designed in England using plastic theory; this included Cambridge’s school buildings and a five-story office building (Beedle, 1955). It is not clearly acknowledged, but it can be inferred that the Morrison Shelter served as a precedent structure in the application of plastic theory. In further studies it should be reviewed if these later applications of plastic theory explicitly reference the Morrison Shelter as a precedent structure.

Although it was not known at the time, because the scope of the development of plastic theory was limited to steel structures, but later it is understood that:

He [Baker] had constructed a theory, the plastic theory, as he thought to discuss the behaviour of steel frames. It turns out that the theory is universal, and can be applied to any material that is used for building (Heyman, 1987)

The influence of plastic theory, which can be applied universally, is foreshadowed by the success of the steel Morrison Shelters.

5.4 Further Work

5.4.1 Explicit Reference of Morrison Shelter as a Precedent Structure

As referenced above in Section 5.3, further research can be conducted to see if others explicitly reference the Morrison Shelter in further development or applications of plastic theory. Specifically, research should investigate the work done by William Prager at Brown University as he collaborated closely with Baker’s team at Cambridge and would
have likely been aware of the Morrison Shelter’s relevance to his own research of the
theory of plastic theory in structures.

5.4.2 Earthquake Desk Application

In reading this thesis, the reader may question so what? Why is this effort taken to
reflect on the significance of plastic theory in the Morrison Shelter? The response is that
there could be future application, similar to that of the Morrison Shelters, which serve as
protective desks for schools in earthquake vulnerable zones. It is noted, that the design
loads caused by air raids are similar to those in earthquakes\(^7\).\(^8\)\(^9\).

Although, there is an entire field studying earthquake engineering and there are
prevention techniques that are much more sophisticated than the steel Morrison Shelter,
the Morrison Shelters are still relevant. 300 million students around the world are
vulnerable in earthquake-prone regions that do not have adequate schools to protect them
in the event of an earthquake (McNicoll, 2013). The students are instructed to hide
underneath their desks, in hope that if the school building comes crashing down, the
desks will provide enough support to protect the students, as was the case in one school
in a recent Mexico earthquake (See Figure 14).

\(^7\) "If a [HE] bomb exploded at some depth in the ground nearby the resulting earth shock often brought down one or
more of the main walls of the house" ("Indoor Shelter", 1941)
\(^8\) "Bombs tended to hit closer than the 50 ft standard – damage from earth shock was a serious factor" (Baker, 1965)
\(^9\) "When a bomb explodes, ... the sudden outward rush of gas in the immediate neighborhood of the bomb and its
subsequent and almost equally violent return, starts a backwards and forwards vibration of the air which is transmitted
to a very considerable distance and has a rocking action on any building within range. In addition, an earth tremor is
generated somewhat like that occurring during an earthquake." (ARP: Incorporated shelters in housing— issued by the
cement and concrete association; Shelters and pamphlets issued to the public 1939-41)
The design criteria for this proposed application of an earthquake-protective desk are very similar to those found in section 4.1 for the Morrison Shelter. They should be lightweight (able to be carried by young school children), easily produced, low-cost and obviously protective in the case of a school’s collapse. This application as a desk is reminiscent of Morrison’s secondary use as a table.

There is criticism of developing this application because it does not fully protect children; a better solution undoubtedly is renovating and replacing vulnerable schools with buildings that are designed to withstand earthquakes and comply with the modern building codes. However, this is not realistically achievable in a short period of time and in developing nations, so in the meantime, these desks are a solution to protect the students who are left vulnerable. It has been estimated that equipping a classroom with earthquake-resistant desks is “ten times cheaper than strengthening its walls, and more
than 400 times cheaper than building a new class/school that is up to earthquake building standards” (Core77, 2012).
6 Conclusion

Although the importance of designing using Plastic theory has been expressed, especially in the context of material savings in the application of the Morrison Shelter and the Baker Building, it is imperative to demonstrate this importance with validation via calculations comparing elastic and plastic designs. With this proof in hand, it is possible to credibly recommend the further application of structures using plastic theory. More research can be done to see how the Morrison Shelters’ success impacted the early application of plastic theory. But, the essence of this thesis is to show that plasticity is a viable and necessary theory used in the design steel table shelters.
Appendices

Appendix A: References


ARP Department Circular No 102/1039. May 5, 1939.


Baker, J.F. “‘Merseyside’ Bedroom Shelter” Correspondence. February 1, 1941.


Bernal, JW to Stradling. “RE 27/28/1.” 1941.


“Home made shelters” RE 10/3/5. 1941.


New Scientist, July 18, 1974.

Pippard, 1968


SSRC


*The Design and Testing of the Table (Morrison) Indoor Shelter*. R.C. 204. Ministry of Home Security Civil Defence Research Committee. May, 1941


F. Webster to John F. Baker. November 8, 1940.
Appendix B: Air Raid Shelter Policy (Cmd. 5932) 1938
Report by: Anderson, Hurst, Japp
Appointed by the Lord Privy Seal to consider certain aspects of the Problem of Air Raid Shelters

AIR RAID SHELTER POLICY

Report by

Mr. David Anderson, D.I.D. B.Sc M.Inst.C.E.
Mr. B. L. Hurst, M.Inst.C.E.
Sir Henry Japp, K.B.E. M.Inst.C.E.

Appointed by the Lord Privy Seal to consider certain aspects of the Problem of Air Raid Shelters

Presented by the Secretary of State for the Home Department to Parliament by Command of His Majesty December, 1938
REPORT TO THE LORD PRIVY SEAL

We have had the opportunity of discussing with the Lord Privy Seal some of the problems of the shelter policy, and in particular the proposal to provide sectional shelters for the population of vulnerable areas in their own homes.

In the first place we would record our whole-hearted agreement with the Lord Privy Seal that the provision of a shelter in or in close proximity to the home of every citizen in vulnerable areas is a sound policy, and that such shelter should provide reasonable protection against blast and splinters from the near-by explosion of a medium-sized H.E. bomb and against the collapse of the super-structure, and we have now to record our opinion as to how far a sectional steel shelter can fulfil the requirements of this policy.

1.—(a) A sectional steel device is one method of providing such shelter. There are a number of such devices on the market and we consider that two or three standard types could be adopted which would satisfy the requirements and which would enable a large number of firms to adapt their plant to the production of one or other of the types with the least possible delay.

(b) Such a shelter should measure not less than 6 feet by 4 feet 6 inches in plan and should not be less than 6 feet high from the crown of the arch to the floor. This shelter would hold four persons for a short period and might even in an emergency hold six persons. It would, therefore, form the minimum shelter for the two-storeyed terraced house or cottage type of modern house, which on the average, accommodates rather under four persons. The dimensions given are in our opinion the absolute minimum for three reasons:

(i) Anything smaller would have no market value above its value as scrap, whereas a structure of the minimum size which we recommend would have a definite value for other useful purposes.

(ii) That there would be serious risk of very rapid suffocation in any smaller shelter in the event of the exits being blocked and

(iii) Anything smaller would be unacceptable to the people and we would particularly emphasize the danger of issuing a type of shelter which could only be entered by crawling and in which only a crouching or recumbent attitude is possible.

(c) The weight of such a shelter would be from 5 cwt. to 7 cwt. and the maximum weight of any one member would vary from 60 lbs. to 100 lbs.
In our judgment these shelters could not be distributed quickly and easily. For every million persons provided for the weight of metal to be handled would be from 00,000 to 80,000 tons or on the average 25,000 lorry loads. The shelters must be distributed by lorries and must therefore be distributed in advance of an emergency owing to the claims upon transport at such a period.

(d) These shelters could be mass-produced and be capable of erection by two men of average strength and no special skill. The design should be confined to two or three types at the most.

II. With regard to the position to be occupied by these shelters we are definitely opposed to the placing of them within houses for the following reasons:

(a) The ordinary ground floor room of the small house only measures about 10 feet by 12 feet and therefore such a room would be to all intents and purposes out of action whilst the shelter was in it. Every air raid will reduce the available accommodation and increase the pressure on undamaged houses in already overcrowded areas, and it is therefore an error to render any accommodation useless for normal purposes.

(b) The shelter would provide no additional protection against splinters beyond that which the walls of the room provide, and would have no resistance to splinters entering through the doors or windows.

(c) Unless the floor of the room were removed and the shelter placed on the ground below (generally about 15 inches below the floor) there is danger of the shelter being driven through the floor by the collapse of the house, to the added danger of the occupants.

(d) Unless the shelter were strongly anchored to the floor, the collapse of one side of the house would incur the risk of its displacement and distortion.

(e) There is a very serious risk of debris from the fall of the house forming a solid wedge of masonry at the ends of the shelter making the rescue of the occupants very difficult. For the same reason there is a risk of the occupants being suffocated from lack of air and by the dust from the debris. The higher the house the greater will be this risk.

(f) Assuming, as seems most likely, that an attack with H.E. bombs will be accompanied by the use of incendiary bombs, the risk that the shelter will become an oven for the trapped occupants is a very real one and one which we consider would render the acceptance by the people of the device for use inside a house more than doubtful.
(g) There is a risk that the entrapped occupants may be killed by the escape of gas from the domestic supply (the gas-mask is not proof against this form of gas).

A shelter device of this kind, to be provided in large numbers must in our judgment satisfy public opinion. Undoubtedly most people would prefer to stay in their houses to take shelter, and though at first sight the device might seem to render this possible, the plain truth is that if they do so, within the protection of such a shelter, their chances of rescue are greatly diminished and the prospect of a lingering death increased if the house collapses. Ease of exit is the most fundamental requirement of a proper shelter and ease of exit from a sectional shelter within a small collapsed house is almost a contradiction in terms.

There is however in our judgment a very definite place in the shelter policy for a steel shelter device of this kind for small houses. During the recent crisis the Home Office recommendation that the householder should dig a trench in his back-yard or garden was severely criticised on the grounds that many could not afford the cost of the materials necessary to revet the trench, and there was a demand for the free issue of material for the purpose.

The sectional device is an answer to this criticism. Placed in the garden or yard and covered with earth or sandbags it provides as good a shelter as a covered trench. It should be sunk at least partially in the ground as this not only provides increased lateral protection but also provides the earth necessary to cover the shelter. Thus protected it can be placed close to the house without serious risk from the collapse of the building.

III. The extent to which the sectional shelter may be regarded as a solution to the problem, and the numbers which would be required if it is adopted, are difficult for us to assess, as we have not the figures at our disposal to show in detail how the population of vulnerable areas is housed. We would recommend that the following principles should be adopted in assessing the extent of its application.

(a) The device is suitable for the cottage type of houses on the modern building estate where there is ample garden space. Owing to the flimsy nature of these buildings it is not easy to strengthen them at reasonable cost in order to provide adequate shelter within the house without considerable disturbance in peace time.

(b) It is suitable for the two-storeyed terraced type of house many of which are old and unsound, provided that there is sufficient room in gardens or back-yards to erect the shelter. From the few enquiries we have been able to make it appears that in the majority of cases in London such back-yards exist. The problem of two-storeyed terraced
houses without yards must, however, not be overlooked and some other solution must be sought for these.

(c) It does not provide the best solution for the basement house, for which we make other recommendations.

(d) It is no answer to the problem of providing shelters for the occupants of tenement flats where hundreds of people are housed in blocks of buildings in which the provision of family shelters is impossible and the provision of communal shelters will be necessary.

IV. We consider that the sectional shelter which will be erected in time of emergency has a definite place in the immediate short-term policy, and will provide a reasonable amount of safety though it is less efficient than a permanent structure of brick and/or concrete, of the pill-box type, which would in addition have a definite peace-time use as a coal-shed, bicycle and perambulator store or garden shed, but which would be more expensive. These would be built in groups at the intersection of fences to accommodate two or four households of four people each.

V.—(a) The provision of shelter in the basement house can best be provided, in our judgment, by propping the basement ceilings and providing adequate alternative exits. It must be remembered that in this type of house there is generally a family on every floor, and in many areas a family in the basement as well, or from 12 to 16 persons in every house. The basement rooms will have to be prepared in peace time to receive the props and some work may be necessary to make the provision of emergency exits possible. This will necessarily involve temporary inconvenience to the basement dwellers, but when the work has been done the basements will be no less habitable than they are at present. The props can be stored and erected by unskilled labour at the time of emergency, but when erected the basements will definitely have to be regarded as refuges for all the inhabitants of the house and the tenants must be evicted.

(b) As regards existing tenement flats, the problem is a very complex one and will have to be investigated in greater detail, but the provision of communal shelters might take several forms such as:

(i) The evacuation of some or all of the ground floor flats (or the basement if such exists) and the strengthening and adaptation in peace time of the portions evacuated. Their use as flats will cease, but uses can be found for them as play-rooms, bicycle and pram-stores, etc.

(ii) The construction of permanent covered trenches in communication with the main buildings.

(iii) The construction of subsidiary buildings with definite protective value which would also have peace-time
VI. Legislation with regard to future residential buildings.

We appreciate the argument that the constant presence of an air raid shelter such as a trench in the garden which has no peace-time purpose may have a possible adverse psychological effect on the minds of children, but so long as air attack remains a definite threat we consider that the absence of a sense of protection will have an increasingly adverse psychological effect on the adult population.

The solution in our judgment must be along the lines of providing in every home an air raid shelter which will provide reasonable protection against blast splinters and the collapse of a super-structure, and which will have a peace-time use and to which the children will be accustomed as part of their daily life and which will therefore not have any sinister connection in their minds, and the entering of which would in war time be no novelty.

To meet this objective we should like to place on record our very strong view that immediate legislation should be undertaken with a view to ensuring that no residential building of whatever size or class should be erected in future without the inclusion therein of an air raid shelter, of sufficient size to accommodate all the inhabitants of the house in reasonable safety. To delay such legislation is only to add to the difficulty in war time of providing refuge accommodation.

Huge programmes of rehousing are being undertaken in our densely populated areas, which must all be considered vulnerable and in course of time the areas of bad housing will all be rebuilt and to fail to take cognizance of the air raid menace in new construction is in our view short-sighted if not worse.

These rebuilding schemes are for the lower-paid class of workers, but we consider that the provision of air raid shelters in better-class residential buildings is equally important.

In time of war essential workers who have been forcibly evicted by the destruction of their homes through fire or by high explosive bombs will of necessity be billeted, like soldiers in a war zone, in the most suitable and safest buildings available in the vicinity of their work. These may, and most probably will be, in the houses of the more well-to-do residents, many of whom will have been voluntarily evacuated, and for this reason we consider that the provision of an air raid shelter in or on every residential property should be compulsory.

VII. When the problem of providing shelter in the home is solved there still remains the problem of shelter for persons caught in the street and for the worker passing between his home and the scene of his labour. As we have already said,
we share with the Lord Privy Seal his doubts with regard to trenches as a solution of this problem, although they must of necessity form a feature of the immediate policy. Trenches, however, cannot be dug in many localities where shelter is most needed, and we would urge most strongly that the policy of providing public shelters in suitable basements adequately strengthened and provided with alternative exits, which was part of the Government policy before the Crisis, should now be zealously pursued. We understand that the duty of making a survey of such shelters and arranging for same was laid upon the Local Authorities, but we consider that if the work is to be done promptly it will be necessary to organise a comprehensive scheme in which the professional bodies of the country will be enlisted to work in conjunction with the Local Authorities and with the organisations of the Public Works contractors and the steel industry. This work is one of enormous magnitude owing to the wide distribution of the work and the amount of detail involved.

VIII. There are three points on which, in our judgment, a very clear pronouncement to the public is essential.

(a) If the goodwill of the public in this problem of providing shelters is to be enlisted there should be a very clear understanding that there will be no penalization in regard to increased taxation and rating on account of the provision of air raid shelter accommodation. In his speech in the House the Chancellor of the Exchequer, on the 28th May, stated that there would be no such penalization. We feel, however, that there is still no clear understanding in the minds of the public on this subject.

(b) With regard to the provision of basement shelters in large shop and office buildings and in the larger private premises, the Committee consider that Building Owners would be encouraged to provide permanently strengthened basements if it were common knowledge that the L.C.C. and other Local Authorities were willing to relax their bye-laws for steel and other materials added to the basement ceilings of existing structures solely for the purpose of rendering them safe to withstand collapse of the building above and the Committee recommend that this should be arranged for. Two such matters which might be instanced are:

(i) That concrete "fire cover" encasement of constructional steelwork added solely for the above purpose might be waived.

(ii) That stresses not exceeding 10 per cent. above normal stresses might be authorized in the previously existing structural steelwork of such buildings, provided that such stress excess were solely due to the
addition of the dead weight of added protective structure.

(c) As regards "pill-box" or other external shelter accommodations the Committee submit that the following arrangements should be made in order to encourage Private Building Owners to construct them at their own cost, viz.:

(i) That concrete "fire cover" encasement of constructional steelwork should be dispensed with.

(ii) That typical designs and estimates of cost should be prepared by the Government and issued to Building Owners.

The Committee suggest that the relaxations of Building Regulations recommended above should form the subject of new Bye-laws, as otherwise every case would have to be dealt with by special application and grant of a waiver, which would not only cause much unnecessary work and delay, but would tend to discourage Building Owners from embarking on schemes.

IX. In conclusion, we would respectfully state our firm conviction that the magnitude and urgency of this problem are so great that the utmost possible use should be made of the resources of every trade that can be employed on the work in the construction of all the forms of shelter accommodation dealt with hereinbefore to the utmost extent and at the utmost possible speed, viz.:

(a) Pressed and rolled sectional shelters.
(b) Propped basements.
(c) "Pill-boxes".
(d) Permanently strengthening lower floors of blocks of flats and tenements.
(e) Permanently strengthened basements of shops, offices and large houses.
(f) Communal shelters and trenches.

Only by these means can we conceive that the necessary accommodation will be made available within a reasonable period of time.

DAVID ANDERSON.
B. L. HURST.
H. JAPP.

20th December, 1938.
Appendix C: Objections to Cmd. 5932 cont.
Appendix D: Shelter Use for Indoors

1. The following points should be borne in mind in considering a shelter for use indoors:
   
   (a) The primary purpose of a shelter is to protect occupants from falling debris, e.g. from the floor above, which usually falls in one piece, from outside walls, which usually subside and from doors, light partitions, etc. which being vulnerable to blast may be thrown about with considerable velocity.
   
   (b) Adequate protection from splinters is supplied by the existing walls of the house. The shelter need not, therefore, provide additional lateral protection, though it should be low enough for the occupants to be below cill level.
   
   (c) As raiding now starts early in the evening, it is desirable that the shelter be of such a height that the occupants can not only sleep in comfort, but sit up during the evening.
   
   (d) Maximum ventilation should be provided.
   
   (e) Easy access for making the bed in the shelter should be provided and ready exit is essential.
   
   (f) The structure of the shelter should not be vulnerable to blast.

2. A drawing of a shelter which satisfies the above conditions is attached. It consists of a rectangular stool framed over with expanded metal designed to withstand without collapse, the following debris loads:

   (i) 320 lb./sq.ft. static load over whole area of shelter.
   
   (ii) The weight of an area of floor 14 ft. x 6 ft. 6 in. by 20 lb./sq.ft. falling flat on the shelter from a height of 6 ft.

   (iii) The same area of floor hinged about one wall falling and striking one edge of the shelter.

   (iv) 160 lb./sq.ft. static load applied to any side.

   The design therefore satisfies (a) above, but the details of connections of expanded metal should be tested to determine the exact form. Conditions (b) and (c) need no comment. With regard to (d) the sides of the shelter are designed to swing, or lift off. They are light in weight and so make access to the inside of the shelter easy and ensure the greatest possible number of emergency exits. Conditions (f) and (g) are provided by the choice of expanded metal sides and top which also enable the ordinary room lighting to enter the shelter.

3. The question of shelters indoors was considered in a report to the Lord Privy Seal "Air Raid Shelter Policy", 20th December, 1938. On page 3, seven objections are given. The following comments on these objections in the light of the design submitted are as follows:-
(a) If the shelter is flat topped it has secondary uses. The proposed shelter with expanded metal walls does not cut down light to other parts of the room seriously.

(b) Statistics show that comparatively few casualties are caused inside houses by splinters. If the shelter is below sill level, there will be no serious danger from splinters.

(c) With an independent floor provided in the shelter there is no danger to the occupants from the shelter being driven into the floor by heavy debris.

(d) There is no risk to occupants from displacement of the shelter and it is designed so that the small distortion possible will not be harmful.

(e) In this shelter all the walls are readily opened forming emergency exits. There is, therefore, the least possible chance of occupants being trapped. This applies also to objections (f) and (g).

Tuesday
17th December, 1940.
JFS/BH.
Appendix E: Design and Testing of the Table (Morrison) Indoor Shelter (R.C. 204, 1941)

1. INTRODUCTION.

It was decided in December 1940 that there should be a Government issue of a shelter to be placed indoors. A design was then called for, and there was, as a result of the knowledge existing of the damage caused to houses by air bombardment, little difficulty in stating the problem and producing a satisfactory design.

The problem was first considered as long ago as December 1938 by a panel of engineers. It was then decided that shelters should not be placed indoors for the following reasons (Command Paper No.5032 "Air Raid Shelter Policy").

(a) The ordinary ground floor room of the small house only measures about 10 ft. by 12 ft. and therefore such a room would be to all intents and purposes out of action whilst the shelter was in it. Every air raid will reduce the available accommodation and increase the pressure on undamaged houses in already overcrowded areas, and it is therefore an error to render any accommodation useless for normal purposes.

(b) The shelter would provide no additional protection against splinters beyond that which the walls of the room provide, and would have no resistance to splinters entering through the door or windows.

(c) Unless the floor of the room were removed and the shelter placed on the ground below (generally about 15 in. below the floor) there is danger of the shelter being driven through the floor by the collapse of the house, to the added danger of the occupants.

(d) Unless the shelter were strongly anchored to the floor, the collapse of one side of the house would incur the risk of its displacement and distortion.

(e) There is very serious risk of debris from the fall of the house forming a solid wedge of masonry at the ends of the shelter, making the rescue of the occupants very difficult. For the same reason there is a risk of the occupants being suffocated from lack of air and by the dust from the debris. The higher the house the greater will be this risk.

(f) Assuming, as seems most likely, that an attack with H.E. bombs will be accompanied by the use of incendiary bombs, the risk that the shelter will become an oven for the trapped occupants is a very real one and one which we consider would render the acceptance by the people of the device for use inside a house more than doubtful.

(g) There is a risk that the entrapped occupants may be killed by the escape of gas from the domestic supply (the gas mask is not proof against this form of gas.)

Wartime experience, which was not available in 1938, has shown that certain of these reasons are not valid. The other objections were overcome, to a large measure, in the final design of shelter shown in Figure 2.
This shelter is a rectangular framework, built of mild steel rolled angles, to which is bolted a 3-in. thick steel plate top. The bottom consists of a steel 12-in. mattress attached to the bottom angles by hooks and hung from studs in the top angles and bearing under similar studs in the bottom angles, in such a way that the panel can be banded either by bending about the top or bottom row of studs.

The shelter overcomes the objections set out in (a) to (g) above in the following way:

(a) The shelter is flat topped and therefore has secondary use as a table. The sides being of open mesh do not seriously cut down light to other parts of the room.

(b) Statistics show that comparatively few casualties are caused by splinters inside houses, and the design prevents the occupants of the shelter from rising above window sill level.

(c) The design incorporates an independent firmly attached bottom, so there is little danger to the occupants from any tendency for the shelter to be driven through the floor.

(d) There is little risk to the occupants from displacement of the shelter by debris, earth shock or blast. There is no large flat vertical surface for blast to act upon and the shelter is designed so that small distortion by debris, etc. will not be harmful.

(e) All four sides of the shelter may be readily opened or removed by the occupants or by rescuers outside, so there is the least possible chance of being trapped. This applies also to objections (f) and (g).

Though it was easy to state the problem and to produce an initial design, the difficulties of supply and mass production in wartime were such that many amendments had to be made before a final approved design could be issued. In this note an attempt is made to set out the data on which the original design was based, and to describe the various amendments which were made before the shelter was finally put into production.

It must be realised that both the design and the testing of this shelter were very rushed, and the design was varied several times to meet the requirements of mass production and availability of materials. Testing and design proceeded more or less simultaneously and, although most of the tests were not made on the shelter components in their final form, yet they did provide much useful design data.

The first design produced was not different in any essential from the final, but the height of the shelter was 4 ft., and top and bottom as well as sides were shown as covered with weldmesh wire panels. It was soon decided, however, that the advantage of more headroom in the shelter must be sacrificed to the need for a secondary use as a table. The height was therefore reduced to 2 ft. 6 in. and, at the Chief Engineer's suggestion, a thin timber top was placed over the weldmesh panel, both to inspire confidence by supplying an apparently solid cover and to make a useful table top. Figure 1 shows the design of the first shelter to be fabricated.

The first serious supply difficulty arose over the wire mesh covering. Wire was in such short supply that it was necessary to confine its use to the side panels. It was considered essential there, not only to make the shelter less vulnerable to blast, but on hygienic grounds. It would have been unfortunate when, according to medical opinion, shelterers probably owe their present immunity to serious disease to the enforced fresh air taken
on the way to and from public shelters, if those sheltering in their own homes had been supplied with almost hermetically sealed boxes. This would have been fore, for the top and bottom. Though this was troublesome, it was only so on account of supply and not of design difficulties.

It was decided to use rolled steel angle sections for the main framework as they could be obtained easily.

The form of collapse constituting the greatest danger to the occupants of a ground floor room, in which a shelter would be placed, is the fall of the first floor in one piece. The necessary data for the design of the main members to resist this collapse can be stated. Corresponding data for the design of the secondary members are not so easily set down. It is difficult to fix the size and distance of fall of the largest piece of debris, etc., likely to strike the top of the shelter, and it is almost impossible to decide the size and velocity of crater debris and brickwork likely to be flung against the sides of the shelter. It was, therefore, considered that the only reasonable basis for the design of the top, side panels and fixings was that they should be capable of developing the full strength of the supporting main members. In other words to ensure that whatever the loading to which the shelter was subjected, failure would occur in the main members.

2. DETAILED DESIGN OF SHELTER.

(a) Design of top angle rails along long sides of shelter.

The greatest dimension of the room in the direction of span of the floor joists in which a shelter is likely to be installed is 14 ft., and therefore the maximum effective area of floor which can strike the shelter is 14t, where l is the length of the shelter. This area of floor may, in some cases, remain horizontal and fall on to the shelter in one piece, but more commonly one or two walls only of the room will be demolished, and the floor will swing down hinging about the surviving wall. This condition also represents more severe conditions for the shelter, since the entire impact is carried by only one of the top longitudinal angles and the blow is inclined to the vertical.

The dead weight of a normal floor consisting of 1 in. tongued and grooved boards on 9 in. x 2 in. joists at 14 in. centres, with a lath and plaster ceiling underneath, is about 16 lb./sq.ft. If an allowance for furniture is made of 350 lb. on the portion of the floor which strikes the shelter, then a total of 50 lb./sq.ft. is reached.

The normal height of ground floor rooms in small dwelling houses is about 8 ft. 6 in. but slightly greater heights may occur.

The conditions for which the shelter has been designed are, therefore, that it should be able to withstand, without injury to the occupants, the fall from a height of 9 ft. of a piece of ceiling measuring 14 ft. by 8 ft. 6 in. and weighing 20 lb./sq.ft. The total energy of the falling floor is, therefore, 145,000 in.-lb.

Only tests could show how much of this energy is communicated to the shelter and how much is absorbed by the floor itself. For the purpose of a rough preliminary design (to be checked by subsequent tests) it was assumed that one half was absorbed by the shelter.

It is, however, quite impossible to absorb this energy elastically, and the members must be designed so that they yield under the impact load and absorb the energy by plastic bending. The load-carrying capacity, and consequently the plastic energy absorption, of a fixed ended beam is rather more than twice that of one simply supported. For this reason, and also from considerations of the lateral strength of the frame as a whole, it was decided to provide rigid joints between the horizontal and vertical members of the frame.
Since the shelter is 2 ft, 8 in. high, it is possible for the side rails to deflect at least 12 in. without causing injury to occupants who are lying down.

With these assumptions the energy absorbed by each of the top rails of the frame will be very approximately equal to \( 16f \frac{2s}{E} \) where \( f \) is the effective yield stress of the material, 16 tons/sq.in., \( s \) is the deflection of the top rail, \( E \) is the modulus of the section of the top rail = 12 in., and \( L \) is the span of the top rail = 6 ft. 6 in. The energy to be absorbed is 35,500 lb.-in. and therefore the modulus of section required is \( \frac{0.35}{s} \) A 3 in. x 2 in. x \( \frac{3}{4} \)-in. angle has a modulus of section of 0.35 in.\(^3\) and this section was therefore originally chosen. Subsequently, however, considerations of supply led to the use of 3 in. x 2\( \frac{3}{8} \) in. x \( \frac{3}{8} \)-in. angles.

To confirm the adequacy of the 3 in. x 2 in. x \( \frac{3}{4} \)-in. angle, the test described in Appendix 1 and illustrated in Figures 3, 4 and 5 was carried out. It will be seen that the actual deflection of the side angle was \( \frac{1}{2} \) in. compared with 8 in. estimated in the approximate calculations above. It should be noted that the shelter, the tests on which are described in Appendix 1, differed from the original design shown in Figure 1 in that the top and side sheeting were composed of expanded metal, and that the corner gussets were welded, not bolted, to the horizontal angle rails. These alterations were made to simplify fabrication and to utilise available material, but they did not appreciably alter the strength of the shelter.

As noted above, the angles have been designed as fixed ended. The safe bending moment on a 3 in. x 2 in. x \( \frac{3}{4} \)-in. angle about its X X axis is 4.15 ton - in. To develop this moment two \( \frac{5}{8} \)-in. diameter bolts are required, their minimum distance apart being 2.7 in.

In the original design shown in Figure 1, end fixity was developed by using bent plate gussets but, to simplify fabrication, in the final design (Figure 2) these were abandoned in favour of using angle verticals of sufficient size, 6 ft. x 6 in. x \( \frac{3}{8} \)-in. to permit of the use of two \( \frac{3}{8} \)-in. bolts at the requisite spacing.

(b) Design of top angle rails along short sides of shelter.

The overall width of the shelter is 4 ft. Worst conditions for the angle rails along the short sides will occur when the shelter is arranged in the room with its long sides parallel to the first-floor joists. Making the same assumptions that were made above in the design of the long sides, it is found that the section modulus required for the short sides is 0.16 in.\(^3\) A 2 in. x \( \frac{3}{8} \)-in. x \( \frac{3}{8} \)-in. angle would, therefore, be sufficient for the vertical loading, but from considerations of lateral strength 2\( \frac{3}{8} \) in. x 2 in. x \( \frac{3}{8} \)-in. angles were proposed, though supply difficulties led to the eventual adoption of 2\( \frac{3}{8} \) in. x 2\( \frac{3}{8} \) in. x \( \frac{3}{8} \)-in. angles.

(c) Design of bottom angle rails.

The principal functions of the bottom rails are to carry the mattress and to increase the lateral stability of the frame as a whole. With these considerations in mind the bottom rails on both the long and the short sides were originally designed as 2\( \frac{3}{8} \) in. x 2 in. x \( \frac{3}{8} \)-in. angles, but supply difficulties subsequently necessitated the substitution of 2\( \frac{3}{8} \) in. x 2\( \frac{3}{8} \) in. x \( \frac{3}{8} \)-in. angles.

(d) Lateral strength of shelter.

In the final design, having 6 in. x 6 in. x \( \frac{3}{8} \)-in. angle verticals with the horizontal rails bolted direct to them, the rails can be assumed as fixed ended beams against both vertical and horizontal loads. The greatest uniformly distributed horizontal load which can be applied to the top rail on the long side is, therefore, 2070 lb. The end reactions from this load are carried by the verticals and top and bottom rails on the short sides acting...
as rigidly jointed box frames. The bending moment on each of these frames is 31,050 lb.-in. From this the section modulus required for the top and bottom rails on the short sides is 0.19 in.³. The 2 1/2 in. x 3 1/2 in. x 3/8 in. angles are, therefore, adequate.

(e) Design of top sheeting.

It was originally intended that the top of the shelter should consist of weldmesh fabric. To obtain an idea of the gauge of fabric necessary to resist the punching and tearing action of a large block of masonry falling on the shelter, the test described in Appendix 2 and illustrated in Figure 6 was carried out. For this test it was intended that the fabric should be rigidly fixed to the frame, but unfortunately the fixing used proved to be insufficiently rigid. This resulted in the weldmesh deflecting further than it would otherwise have done. However, the weight did not tear through it, adequately fixed it would have been entirely satisfactory.

Limitations in the supply of wire subsequently necessitated the abandonment of weldmesh fabric for the top covering. The use of black steel sheet fixed to the frame as shown in Figure 8 was considered. A preliminary test, described in Appendix 3 and illustrated in Figure 7, was made on this method of fixing, which proved to be eminently satisfactory. It will be seen that with studs at 10 in. centres the sheeting carried a load of 2,860 lb. per foot run. Since the maximum uniformly distributed horizontal load that can be carried by the top side rails is only 320 lb. per foot run, it will be seen that this fixing would develop their full strength.

To determine the adequacy of the sheeting to resist tearing it was decided to subject it to the test described in Appendix 4 and illustrated in Figures 8 and 9#. Unfortunately in the time available it was impossible to obtain one sheet large enough to cover the shelter, and the top had to be made up out of four separate sheets. Needless to say this considerably weakened it, but even so it will be seen that it showed no tendency to tear and any occupants of the shelter would probably have been uninjured.

However, it was thought that the very economy of this top might make it appear unsatisfactory, as without intermediate stiffeners it could be drummed, like the bottom of a biscuit tin.

To overcome this and give rigidity to the sheet the possibility of using a corrugated sheet was considered, turning the top angles of the frame upside down to house it securely. Had this solution been adopted it would have meant, of course, that a false flat top would have had to be provided before the shelter could have been used as a table. Fortunately it was not necessary. The supply position, which had been difficult all along the line, proved most helpful as, when the matter was discussed with the Steel Control, it was found that a quantity of 3/8 in. thick steel plate was available. As it was more convenient to the Control to release that plate than corrugated sheet, all parties to the transaction were, for once, satisfied. The top was made, therefore, of 3/8 in. thick steel plate which, of course, on a 4 ft. span, was very rigid and strong. This was tested in the same way as the 22 gauge top, and the results of the test are described in Appendix 5 and illustrated in Figure 10.

The only satisfactory way to fix the plate top to the angle frame appeared to be by means of bolts, but as these were in short supply it was essential to use the minimum number. Sixteen 3/8 in. diameter sheeting bolts were first tried, as these were, in somewhat freer supply than structural bolts. However, the tests described in Appendices 6 and 7 all indicated that these bolts were insufficiently strong, and they were therefore replaced by 5/8 in. diameter structural bolts.

* not reproduced.
(f) Design of side sheeting.

The test described in Appendix 2 showed that No.12 S.W.G. weldmesh with a 3 in. x 1 in. mesh was strong enough to develop the full strength of the top angle rails. This mesh was therefore proposed, in the first place for the sides.

The fixings are shown in Figure 8 and it will be seen that they fulfill the dual function of securing the top sheet and forming hinges for the side sheets. To stiffen the sheeting and to avoid an undue number of studs, it was proposed to use a No.5 S.W.G. margin bar at the top and, bottom of the sheet. Production difficulties unfortunately ruled this scheme out, and to compensate for the lack of margin bars and to reduce the danger of the panels being bent by rough usage, No.10 S.W.G. weldmesh was used. Manufacturing difficulties, and the substitution of the 1-in. plate top for the 22 gauge sheet, necessitated a redesign of the studs, the final form of which is shown in Figure 2.

In addition a hook and eye fastening, also shown in Figure 2, was provided between adjacent panels, so that the occupants could fasten them once they were safely inside the shelter. This ensures that the edges of the weldmesh panels are in close contact with the faces of the top and bottom angles. When debris strikes the side of the shelter the edges of the weldmesh will engage with the studs at top and bottom and an efficient screen will thus be provided.

(g) Design of bottom.

The functions of the bottom of the shelter are:

1. to spread the reactions resulting from debris load on the shelter over as large an area of floor as possible and so reduce the danger of the shelter being driven through the floor,

2. to prevent the floor boards from being driven into the shelter should it be forced through the floor,

3. to ensure that the occupants will be carried safely inside the shelter should it be moved bodily by debris,

4. to give added comfort to the occupants.

When it was found impossible to obtain weldmesh for the bottom, a very effective substitute was developed in the form of an old-fashioned lath mattress. The laths were of 22 gauge sheet 2 in. wide, bent over the bottom angle at the ends and secured to it by the side panel studs, which thus had a dual purpose.

Unfortunately, the bent ends would have made bundling difficult and would have put up the cost of transport; this form of mattress was therefore regrettfully abandoned.

The mattress finally selected was made up of laths attached to the horizontal legs of the bottom angles by hooks and springs. Though not as strong as the original lath mattress, it was considered reasonably satisfactory and could of course be bundled and put together easily.
APPENDIX 1.
"Falling Floor" Impact Test.

1. Shelter tested.

The shelter tested was as shown in Figure 1, except that the gussets connecting the horizontal rails to the verticals were welded to the latter with two 3/8-in. diameter bolts and the top and side sheets consisted of No.19 "Expamet" (2 in. by 3/8-in. mesh, strips 3/8-in. wide by No.16 gauge). Neither of these differences would have any appreciable effect on the strength of the shelter.


Figure 3 shows the general arrangement of the test. The shelter was placed on a concrete floor and prevented from moving laterally by a timber strut and bearer. The test load consisted of a system of parallel floor joists loaded with sandbags, to provide a total of 1820 lb. (10 lb. per sq.ft.) The free ends of the joists were connected together by an 8 in. x 3 in. timber nailed to each joist. The test floor was hinged at one end and rested on a movable bearing at the other. The latter bearing was removed, allowing the floor to swing down and strike the top of the shelter.

This test was designed to simulate the conditions which would arise if the shelter were on the ground floor of a house, one of whose walls was demolished by a near bomb explosion. It should be noted that this represents about the worst possible conditions for the shelter. The fact that the shelter is on a concrete floor and is prevented from moving laterally means that it will absorb more of the energy of the falling floor than it would do if placed on a more resilient timber floor and left free to move horizontally. Moreover, the fact that the test floor swings down about one end results in the shelter being more severely tried than would be the case if the entire floor fell in one piece and remained horizontal. In the latter case the total energy of the falling floor would be double that of the test floor, but this energy would be divided equally between both the top side rails of the shelter. Moreover, in the case of the whole floor falling, the load would be applied vertically to the side rails of the shelter and these are appreciably stronger against a vertical load than against one inclined to the vertical.

3. Result of test.

The falling end of the test floor struck one of the top longitudinal angles causing it to bend down and in, as shown in Figure 4.

It will be seen that the shelter was strong enough to absorb the energy of the falling floor and that, had the shelter been occupied, no injury would have been caused to the occupants. Moreover, of the four exits from the shelter, only the one on the side that was hit suffered any damage.

APPENDIX 2.
"Falling Mass of Masonry" Impact Test.

1. Shelter tested.

The shelter tested was similar to that shown in Figure 1, except that the top consisted of No.5112 weldmesh, i.e. 3 in. by 1 in. mesh with No.12 gauge wires welded at all intersections. The mesh was fixed by clamping it all round with 1 in. by 3-in. flats bolted at 12 in. centres to the horizontal legs of the top angle rails. The side sheeting panels were omitted since they could have no effect on the test.

It was estimated that the largest piece of masonry likely to strike the shelter as a result of damage to a typical dwelling house, would weigh about 3 cwt. If such a piece of debris fell from a wall above first floor level, its fall would be arrested by that floor; even if it penetrated, its velocity would be considerably reduced. It was therefore considered that worst conditions for the shelter would be represented if the piece of debris were allowed to fall freely from a height corresponding to first floor level in a normal dwelling house.

To simulate the conditions envisaged above, a solid mass of concrete about 2 ft. 6 in. by 1 ft. by 1 ft., weighing 364 lb., was suspended over the centre of the shelter, the centre of gravity of the mass being 9 ft. above floor level. The mass was released and allowed to fall freely on to the shelter.

3. Result of test.

The impact of the falling mass of concrete caused the long side angles of the top frame to deflect inwards and downwards as shown in Figure 6. In addition, the mesh was torn off its fixings to the short side angles. However, the weight was held with a minimum clearance above the mattress of 1½ in. and it is possible that occupants of the shelter would have been uninjured. Had the mesh been more securely fixed to the short side angle rails it is probable that the deflection would have been considerably reduced.

This test showed that the mesh and the frame were adequate, but indicated that more attention should be paid to the fixing of the mesh to the frame.

APPENDIX 3.

Test of method of fixing flat top sheet.

1. Method of test.

The purpose of this test was to find out whether the proposed method of fixing the top sheeting shown in Figure 8 would enable it to develop the full strength of the top angle rails.

A specimen was made up as shown in Figure 7 and was tested in tension.

2. Result of test.

The test specimen carried a load of 10,680 lb. without any apparent effect on either the sheeting or its fixings. The test was then discontinued because the ½-in. bolt, through which the load was applied, began to pull through the web of the 5 x 2½ channel.

This load represents 1780 lb. per stud, so that with studs at 12 in. centres, as in Figure 8, the sheeting could apply a horizontal load to the top angle rails of 12,560 lb. Since these angles would yield under a horizontal load of 2070 lb., it will be seen that this method of fixing is adequate.

APPENDIX 4.

"Falling Floor" Impact Test on 22 gauge Top Sheeting.

1. Shelter Tested.

The shelter tested was similar to that shown in Figure 1, except that the side and end sheets of B.R.C. fabric were omitted and the top sheet consisted of four widths of 22 gauge flat black steel sheet arranged as shown in
Figure 8. It was intended that the top of the shelter should consist of a single 22 gauge sheet, but unfortunately a sheet of this size was unattainable in the time available.


The general arrangement of the test was similar to that described in Appendix 1, except that in this case the shelter was arranged so that the ends of the floor joists would strike the top sheeting.

3. Result of test.

The falling end of the test floor struck the sheeting, causing it and the supporting angles to deflect as shown in Figures 8 and 9. The test load was held at a minimum distance of 1 ft. 3 in. above the mattress and the sheeting showed no tendency to tear. It should be noted that, had the top been composed of a single sheet, the deflection would have been reduced.

APPENDIX 5.

"Falling Floor" Impact Test on 1/4-in. Plate Top Sheet GST.

1. Shelter tested.

The shelter tested was similar to that shown in Figure 1, except that the top sheet was of 1/4-in. mild steel plate fixed to the frame by means of sixteen 5/16-in. diameter sheeting bolts. The side panels were omitted.


The arrangement of the test was identical with that described in Appendix 4.

3. Result of test.

The top plate was deflected a maximum of 5 1/4 in. and it caused the supporting angles to deflect down and in, as shown in Figure 10. Two sheeting bolts in each corner were sheared off.

It should be noted that, had the top been composed of a single sheet, the deflection would have been reduced.

APPENDIX 6.

Test on Shelter as Proposed for Mass Production.

1. Shelter tested.

The shelter tested was identical with the final production model shown in Figure 2, except that sixteen 1/4-in. sheeting bolts were used to fix the top plate in place of the 3/8-in. structural bolts finally used.


The shelter was successively subjected to the "Falling Mass of Masonry" impact test as described in Appendix 2, and the "Falling Floor" impact test as described in Appendix 1.

3. Result of test.

The results of the tests are shown in Figures 11, 12 and 13. It will be seen that the 1/4-in. sheeting bolts were sheared by the falling mass of masonry, but in spite of this, the deflection of the top sheeting was only

* not reproduced.
4½ in. and any occupants would have been quite safe. It will also be noticed that the framework is much stiffer than in the earlier shelters tested due, of course, to the substitution of 6 in. x 6 in. x ½-in. angle verticals for the original 2½ in. x 2½ in. x ½-in. angles. This has resulted in the maximum deflection of the top angle rail being only 4 in. as compared with 6½ in. for the test described in Appendix 1. The increased stiffness of the verticals is probably also the reason why one of the ½-in. diameter bolts fixing the top angle rail to the vertical has sheared. This bolt failure is not, however, dangerous. As soon as one of the two bolts fails, the top angle rail becomes simply supported instead of fixed ended, and the stresses in the surviving bolt are considerably reduced.

APPENDIX 7.

Demolition at Hammersmith of Two Storey Semi-Detached House.

1. Shelter tested.

The shelter tested was identical with the final production model shown in Figure 2, except that sixteen ¼-in. sheeting bolts were used to fix the top plate in place of the ⅛-in. structural bolts finally used. Two dummy figures were laid in the shelter on an overlay mattress supported on the ⅛th mattress of the shelter.


Figure 14 shows the general arrangement of the test. The shelter was placed on the ground floor in the front room of a semi-detached house built about 1914.

Construction of the house.


The outside was rendered from 3 ft. 3 in. above ground level.

Floors. Ground Floor. 4 in. x 2 in. joists at 15 in. centres on 4½ in. brick sleeper walls. ¾-in. boarding. First Floor. 6½ in. x 2 in. joists at 15 in. centres spanning from front to back. ¾-in. boarding.

Roof. Timber framing covered with Marseilles tiles.

Window Frames. Wood.

Explosive.

The charge of 40 lb. gun cotton was placed round the front and back rooms, ground floor, at skirting level. Sandbags were placed outside the window to avoid damage to adjoining property.

The adjoining house was shored to insure that the maximum amount of debris fell on to the shelter.

3. Result of test.

(a) Damage to house. The house was completely demolished. The external walls fell outwards, the party wall, the first-floor complete and the roof timbers fell on to the shelter, the height of the resulting debris being about 10 ft. above ground level. The front chimney stack was broken into pieces which were blown into the front garden. The first floor joists were lying on their sides across the shelter.

(b) Rescue. About five minutes after the demolition of the house, a rescue party arrived on the scene. After about an hour's work, which included sawing through a number of floor joists, they had cleared the debris from the shelter sufficiently to permit them to extricate the dummy figures. The condition of the shelter at this stage and the rescue of one of the dummies, are shown in Figure 15.
(c) Damage to shelter. The shelter was moved diagonally a distance of about 3 ft. as shown in Figure 14.

The sixteen 3-in. sheeting bolts fixing the top plate to the frame had failed, allowing the top plate to move sideways relative to the frame. The exact amount of this movement of the top plate is uncertain, as it may have been increased by the clearance operations subsequent to the rescue of the dummies, but it was certainly sufficient to permit a certain amount of debris to fall into the shelter.

The failure of these bolts was almost certainly due to the blast from the explosive charge, which may well have been comparable with that of a small bomb bursting in the same room as the shelter. Although it was realised that this represented more severe conditions than the shelter could be expected to resist, nevertheless taken in conjunction with the bolt failures in the tests described in Appendices 5 and 6 it was decided that the fixing of the top plate was inadequate. The design of the shelter was therefore amended, the sixteen 3-in. sheeting bolts being replaced by sixteen 3-in. structural bolts.

The angle framework of the shelter was bent as shown in Figures 16 and 17. There are two points of particular interest in this connection. One is that one of the top angle rails of the shelter was deflected a maximum distance of 8 in. compared with the 4 in. deflection obtained in the test described in Appendix 6. This rather indicated that conditions in a demolished house might be considerably more rigorous than in the "Falling Floor" impact test. For this reason the weight of the test floor was increased from 1800 lb. to 3000 lb. in the apparatus subsequently designed for the testing of proprietary indoor shelters. The other point which should be noted is that the bottom angle rails of the shelter were considerably bent. This was due to the shelter being driven through the floor on to a sleeper wall and it shows the vital importance of substantial mattress framing.

The weldmesh side and end panels were little damaged and had prevented debris from entering the shelter. One side and one end panel were appreciably bowed in, and one side panel had been cut away by the rescue party to release the occupants.

Although all the hook and spring fixings had failed, the mattress had functioned fairly satisfactorily and had probably prevented the splintered floor boards from being driven into the shelter. The whole mattress was curved up fairly uniformly to a maximum distance of 9 in.

APPENDIX 8.

Demolition at Hendon of Two Storey Terrace House.

1. Shelter tested.

The shelter tested was the final production model shown in Figure 2.

A dummy figure was laid in the shelter on an overlay mattress supported on the lath mattress of the shelter.


Figure 18 shows the general arrangement of the test. The shelter was placed on the ground floor in the front room of the end house of a terrace built about 1900.

The house had been fairly seriously damaged by a previous incident, most of the slates had been stripped and all furniture removed. To compensate for the weight of these items 12 cwt. of bricks were laid on the first floor, in the room over the shelter, and a further 12 cwt. in the back bedroom.
(a) Construction of the house.

First Floor. External 8 in. brick. Internal stud partitions.

Floors. Ground Floor. 4 in. x 2 in. joists at 18 in. centres on 4½ in. brick sleeper walls. ½-in. boarding.
First Floor. 7 in. x 2 in. joists at 15 in. centres spanning from back to front and carried across the bay window and over the central partition on 7 in. x 2 in. trimmers carried on 4 in. x 3 in. wood posts. ½-in. boarding.

Roof. Timber framing covered with slates.

Window frames. Wood.

(b) Explosive.

A total of 15½ lb. of P.A.G. was used, placed as shown in Figure 19. Further details of the method of placing and firing are fully reported in section (C), R.E.2 and 4 Note 6 "Tests on Indoor Shelters".

3. Results of test.

(a) Effect on house. Figure 19 shows clearly the result of the explosion, which caused complete demolition of the house. The majority of the brick rubble from the 9 in. external walls fell on the pavement rather than inside. Some 3 ft. to 4 ft. of wall was left standing below the radius of influence of the charges. Debris was confined almost exclusively to an area not exceeding 12 ft. distance from the original building line.

(b) Rescue. Photos 21(1) and (2) were taken immediately after the explosion, and before any clearance had been undertaken. It will be seen that one side and one end of the shelter were quite clear of debris, and any occupants would certainly have been able to escape unaided.

(c) Effect on shelter. The first floor fell more or less intact on to the shelter, hinging down about the party wall and striking the shelter along its edge remote from the party wall. Conditions assumed in the earlier tests were thus reproduced very closely.

Figure 20 shows the damage to the shelter. It will be seen that the maximum deflection of the top angle rail was only 2½ in. and that the ½-in. bolts proved adequate to hold the top plate in position. As was the case in the test described in Appendix 7, the shelter was driven through the floor, pulling the majority of the springs and hooks from the metal lath mattress and slightly bending one of the bottom angles of the framework.

The weldmesh side panels of the shelter proved adequate to prevent the entry of any large debris into the shelter.

May 1941.

1889(14.5.41).
Appendix F: Story of Morrison Shelter

The Story of the development of the Morrison Shelter is chronicled by Professor Baker in his book *Enterprise versus Bureaucracy*. An overview of the findings from *Enterprise versus Bureaucracy*, Donoughue’s *Herbert Morrison: Portrait of a Politician*, and Baker’s notes found in the Churchill Archives Centre.

Churchill, concerned with the hardship of air raids on civilians, ordered Mr. Morrison, the current British Home Ministry Secretary, “Herbert, you must give the people a shelter in their own homes” (Baker, 1965). Churchill then took an envelope from his back pocket, sketched a gothic-inspired arch and handed to Morrison suggesting the shelter look something like his sketch.

After this interaction, efforts within the Home Security Ministry were made to actualize Churchill’s vision. The Chief Engineer of the Ministry contacted Professor Baker, saying something like this: “Baker, we’ll have to do something about an indoor shelter, the Prime Minister is on our track. Will you come up and help me choose one [of the submitted indoor shelter designs]?” Baker responded by suggesting he design his own that was designed “to behave properly” (Baker archived document). Baker along with his engineering colleagues DC Burn and E Leader-Williams designed the indoor shelter, which was named the Morrison Shelter, with a light steel frame that exhibited the strength of plasticity.

Baker submitted his preliminary design, but simultaneously Dr. Merman within the department was developing a shelter that more closely resembled Churchill’s arched sketch. Baker took development of his design into his own hands because it was being
overlooked since the department was pursuing the arched shelter. Baker made a prototype of his flat-topped shelter with the Forest Products Research Laboratory.

January 1, 1941, both shelter mockups were brought to No 10 Downing Street for Prime Minister Churchill’s approval. Baker was concerned his shelter would not be shown properly to the Prime Minister so he attended the meeting. At the review, “Churchill came into the room and first looked approvingly at the arched shelter, whilst actually sitting on top of [Baker’s]” (Donoughue, 1973). Baker brought attention to his own shelter design, which was had such convenience as an article of furniture, which is why Churchill felt so incline to sit upon it. Baker within ten minutes described the plastic theory that his design exhibited and how it responded to the concerns of command paper 5932. Churchill gave his approval for the production of both shelters. In January the Cabinet authorized an initial production order of 400,000 ‘steel table shelters’ (Donoughue, 1973). Baker saw additional flaws in the design of the curved shelter:

It was a steel shelter, in cross-section the shape of a Gothic arch, with ribs of bent rolled-steel section covered with quarter inch thick steel plate and with steel plate flaps closing the ends. It obviously did not satisfy any of the specifications for an indoor shelter. It was, in effect, a sectional shelter, which the Command Paper had rightly described as a death trap. (Baker, 1978)

Ultimately, the arched shelter was ruled out because of difficulties in mass-producing a curved steel member. It also clearly did not perform as well as Baker’s design after its design had been refined for mass production because its corrugated sides and top were abandoned in value engineering.

Baker’s Morrison Shelter design proved successful. With over 1,174,201 produced and countless lives saved. Years later, Baker encountered Morrison in a pub in
Cambridge. When the topic of the Morrison Shelter came up, Morrison “went silent, blinked rather bewilderedly, and said ‘but I thought I designed it’” (Donoughue, 1973). Despite this confusion, possibly due to Morrison’s old age, Baker was acknowledged as the designer of the Morrison Shelters by the Royal British Academy and named Baron of Windrush as a result of his contributions to saving British civilian lives during the war.
Appendix G: Sample Calculations

Elastic Member Sizing Calculation – Top Side Angle of frame (uniform loading)

Loading: 320 lb/ft²  Area: 6’-5” x 3’-11.75”  Total loading: 8,200 lb

Since there are to portal frames in parallel half of the tributary area is distributed to each side; thus 4,100 lb are loaded on a single bay.

Distributed load: \( w = \frac{4100}{6’-5”} = 53.25 \text{ lb/in} \)

The max moment occurs at midpoint of frame: \( M_{\text{max}} = 38,950 \text{ lb-in} \)

Baker states in the Steel Skeleton v1, after his recommendation to the British Steel Association in 1929, the allowable stress of steel was increased from \( f = 8 \text{ tons/in}^2 \) to \( f = 10 \text{ tons/in}^2 \). This change is applicable to the Morrison Shelter, which was designed in 1941.

The maximum moment and the allowable stress are inserted into the following equation to find the \( S \), which is the elastic section modulus.

\[
M_y = S \cdot f
\]

\[
S_{\text{req}} = \frac{M_y}{f} = \frac{38,950 \text{ lb-in}}{20 \text{ ksi}} = 1.95 \text{ in}^3
\]

The chosen angle was the lightest found section that had an elastic section modulus that exceeded 1.95 in\(^3\). The top-side angle, assuming uniform loading, is 5” x 3” x 3/8”. L 5x3x3/8 has an elastic section modulus of 2.24 and weighs 9.8 pounds per linear foot.

Elastic Member Sizing Calculation – Top End Angle of frame (uniform loading)

Loading: 320 lb/ft²  Area: 6’-5” x 3’-11.75”  Total loading: 8200 lb

Distributed load: \( w = \frac{4100}{3’-10.75”} = 87.7 \text{ lb/in} \)

The max moment occurs at midpoint of frame: \( M_{\text{max}} = 23,959 \text{ lb-in} \)

\[
S_{\text{req}} = \frac{M_y}{f} = \frac{23,959 \text{ lb-in}}{20 \text{ ksi}} = 1.2 \text{ in}^3
\]

The chosen angle was the lightest found section that had an elastic section modulus that exceeded 1.2 in\(^3\). The top-end angle, assuming uniform loading, is 5” x 3” x 1/4”. L 5x3x1/4 has an elastic section modulus of 1.53 and weighs 6.6 pounds per linear foot.
Appendix H: Morrison Shelter List of Parts: Handwritten annotation of weights of parts

THE MORRISON SHELTER
LIST OF PARTS

Uprights or Legs:
Four 6 in. by 6 in. steel angles each 2 ft. 5 in. long (marked 1).  

Top Side Rails:
Two 3 in. by 2 1/4 in. steel angles each 6 ft. 4 in. long (marked 2).

Bottom Side Rails:
Two 2 1/2 in. by 2 1/2 in. steel angles each 6 ft. 4 in. long (marked 3).

Top End Rails:
Two 2 1/2 in. by 2 1/2 in. steel angles each 3 ft. 10 1/2 in. long (marked 4).

Bottom End Rails:
Two 2 1/2 in. by 2 1/2 in. steel angles each 3 ft. 10 1/2 in. long (marked 5).

Top of Shelter:
One 1/4 in. thick steel plate 6 ft. 5 in. long, 3 ft. 11 1/2 in. wide. (marked 6)

Covering for Sides of Shelters:
Two panels of welded wire mesh each 5 ft. 4 in. by 2 ft. 3 in.

Covering for Ends of Shelter:
Two panels of welded wire mesh each 2 ft. 10 in. by 2 ft. 3 in.

Mattress:
Twelve steel laths each 3 ft. 4 1/4 in. long.  
Six steel laths each 5 ft. 9 1/4 in. long.

Mattress Fixings:
Eighteen coil springs.  
Eighteen hooks.

Bolts and Nuts:
Sixteen 3/8 in. diameter nuts and bolts 3/8 in. long (for fixing top plate to frame).  
Thirty-two 3/8 in. diameter nuts and bolts 1 1/2 in. long (for fixing top and bottom angle rails to uprights).

Studs for Holding Welded Wire Mesh Sides in position:
Forty-eight 1/4 in. diameter nuts and bolts 1 in. long.  
Forty-eight washers 1 in. outside diameter.  
Forty-eight tube distance-pieces 1/8 in. long.

Fastenings:
Four hook and eye fastenings (fixings for welded wire mesh sides).

Tools:
One double ended spanner 1/8 in. and 1/8 in.  
One 1/4 in. spanner with pointed handle.  
One drawback ("button-hook") for fixing mattress springs.
Appendix I: Testing on Morrison Shelters

Figure 15: Test Set up for ‘Falling Floor’ Impact Test on Indoor Shelter

Figure 16: Photograph of test set up

Figure 17: Falling floor impact test
Appendix J: “Merseyside” response; load clarification

0/Gen/74/748.

ELW/AR.

1st February, 1941.

Dear Sir,

Your correspondence with Sir Alexander Rouse re the
"Merseyside" bedroom shelter, has been passed on to us for our
opinion as to its strength.

We note that in your letter of 18th January, you say
that "The shelter is designed to take the weight of the floor
and roof above you if your house should collapse". You do not
state what gauge of tubing you propose to use, but it appears
to us that the safe distributed load on the top tubes along the
long sides of the shelter represents a load of only about 30
lb. per sq.ft. of the shelter.

The load to which an indoor shelter is liable to be
subjected is, of course, uncertain. Experience of a large
number of cases of damage to domestic dwellings has, however,
led us to the conclusion that the most probable eventuality
is the demolition of one or more of the walls of a room, leading
to the collapse in one piece of the 1st floor. This floor will
then hinge down about a surviving wall and strike the shelter
obliquely. We have done a number of tests on various indoor
shelters struck in this way by a falling floor and it appears
that, if the shelter is to withstand this impact loading, it
should be designed for a vertical load of about 200 lb. per
sq.ft. and a horizontal load of about 100 lb. per sq.ft.