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Rat-trap masonry: state-of-the-art review

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ABSTRACT

Adequate Shelter is one of the basic needs of all humans. To provide this basic need, building industry throughout the world, specifically in the underdeveloped countries, are moving towards cost effective and energy efficient construction techniques. Rat-Trap Bond (RTB) is one such technique where bricks are laid on their edges vertically with three inches cavity between them. This arrangement has many advantages like cost reduction of up to 30 %, better thermal insulation, dead load reduction, and better aesthetic look. The bond is successfully adopted over the last three decades in Pakistan, India, Nepal, and Sri Lanka for the construction of one and two storey buildings. Several experimental and numerical studies have been conducted over the last two decades to study the cost effectiveness, energy efficiency, thermal insulation, compressive strength, and in-plane and out of plane behaviour, seismic behaviour, and failure modes. This paper presents a comprehensive review of the existing research work carried out on rat-trap masonry.

1. Introduction

Brick masonry is used as the main structural and non-structural component in the construction of buildings in some regions of the world [1]. Many cultures throughout the world have various construction systems which may be categorized as "masonry" structures. Masonry has many variations based on the type and shape of materials along with construction methods. The masonry units may be stones, burnt, or unburnt clay bricks or blocks. Brick masonry is a good choice to be used as a structural material because of good mechanical properties, durability, and comfort. The strength of brick masonry depends on mortar thickness, cement-sand ratio, material type, workmanship, and bond patterns. Various bond patterns used in brick masonry are English, Flemish, stretcher, header, stack, and rat-trap bond.

Bond patterns affect the appearance and other mechanical properties of masonry. This paper discusses the developments made in the rat-trap bond over the past few decades. RTB is a type of brick masonry bond in which alternate headers and stretchers are laid on their edges resulting in a 3-inch cavity inside the wall. The thickness of the wall remains 9 inches as in regular brick masonry. The stretchers laid on the edges are called shiners while the headers on the edges are called rowlocks. The visible face of the wall consists of rowlocks and shiners. In general, the first course, courses below the sill and above lintel level are laid as a solid course of rowlocks. Depending on seismic requirements and design considerations, the T-junctions and the comers can be easily reinforced. Fig. 1 shows various typical layouts and construction details of RTB.

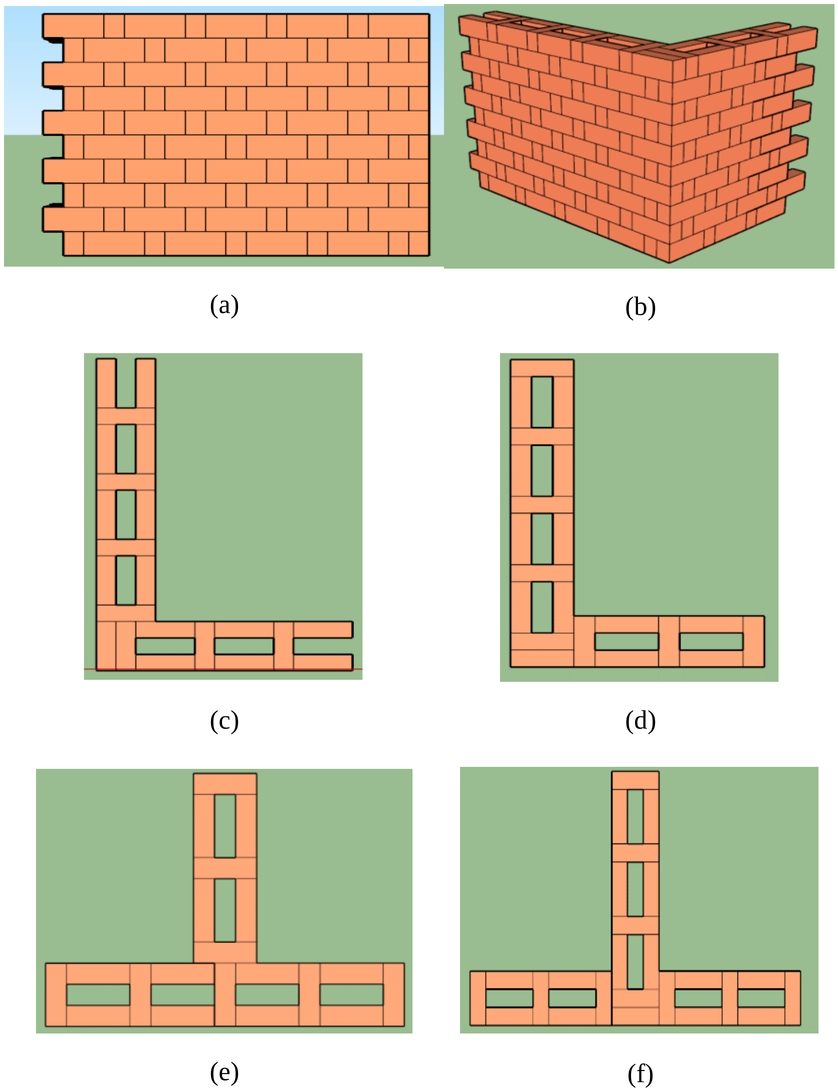


Fig. 1. Construction details and layouts of RTB (a) front view of RTB wall (b) typical arrangements in RTB (c) L joint in RTB first course and (d) second course (e) T joint in RTB first course and (f) second course

1.1 History of Rat-Trap Bond

Rat-trap Bond masonry was used in England till the start of the 20th century for one and two storey buildings as shown in Fig. 2. However, Dizhur and Ingham reported that the RTB construction technique did not gain popularity in the United Kingdom [2]. The brick industry owned by the capitalists opposed the use of economical rat-trap bond as a load bearing wall and promoted the costly and traditional English and Flemish bonds. Therefore, the rat-trap Bond disappeared from the construction industry for years. Later on in the 1970s, a British architect Mr. Laurie Baker re-introduced the rat-trap bond in Kerala, India while working on cost effective housing in India [3]. Many buildings were constructed in India using RTB masonry. This prompted an interest from the construction industry towards research in the RTB technique. The Anna University in Chennai started experiments on rat-trap bond and Sivakumar A. completed his M.E thesis on the rat-trap bond wall in 1995 [4]. Since then, the neighbouring countries like Pakistan, Sri Lanka, Nepal, and Russia also started research work on various aspects and properties of rat-trap bond. They also started construction of various buildings using RTB masonry. Recently the work of Medvedev et al. [5] justifies the use of RTB masonry in Russia.

1.2 Recent Developments in Rat-trap Bond

RTB masonry became part of the National Building Code of India in 2016. Different clauses related to general construction guidelines, materials selection, inspection guidelines, precautions, testing methods, and places where RTB masonry can be used are discussed [7]. It can be used more efficiently in plain areas as compared to hilly areas [8]. It is also categorized as cost effective, thermal and energy efficient, and green building technology. In Nepal, vertical shaft brick kiln/cost effective social and environmental friendly (VSBK/CESEF) has developed an RTB manual document [3]. The manual briefly discusses the guidelines for the use of rat-trap bond in Nepal. After being proposed by the department of urban development and building construction Kathmandu, it was approved by the government of Nepal as an alternative construction technology for earthquake resistant houses [9]. It has also been considered in government norms, standards, and official occupational profile of the Nepal Skill-Test Board (NSTB) [10]. Presently, more than a hundred buildings (residential, hospitals, schools, commercial) have been constructed using RTB technology. Similarly, in Sri Lanka, an NGO named "Practical Actions" in collaboration with a local community based organization called “rural centre for development" has adopted the rat-trap bond for the last 20 years. They have also developed a technical guide [11]. India has constructed hundreds of schools and houses using Laurie Baker guidelines for rat-trap bond [12]. In Pakistan, a foreign nongovernmental organization “IMC Worldwide” [13] has adopted rat-trap bond for the construction of hundreds of schools under the project titled “HAMQADAM” [14].

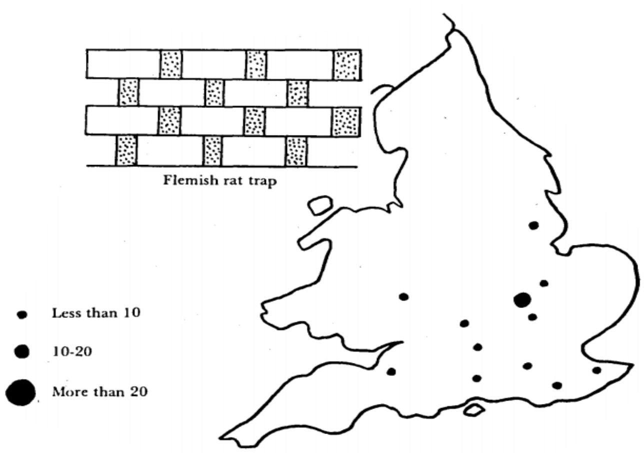


Fig. 2. Map showing usage of RTB in England and Wales in 1970s [6]

1.3 Advantages of Rat-trap Bond

Rat-trap bond has the following advantages over conventional solid brick masonry.

1. Buildings constructed with RTB are energy efficient. Joshi et al. [12] reported that the calculation of embodied energy shows 28% energy saving for rat-trap bond. He claimed that this is equivalent to 13612 kWh of electricity, 1.17 metric tons of oil saving, 13.6 tonnes of CO_2 released to the environment.

2. By adopting this method of bonding, it is possible to reduce the cost of the building by approximately 25 % [12, 15–17].

3. The walls reduce approximately 20% of dead load leading to an economical foundation design [12].

4. Vertical wiring and plumbing can easily be made during the wall construction and even after since, the cavities allow inserting the fittings.

5. Rat-trap Bond is a modular masonry system, which can reduce wastage of bricks by un-necessary cutting.

6. The Cavity adds up the advantage of thermal comfort [14].

7. The frog of the brick faces the internal cavity resulting in finish of both surfaces which provide a better aesthetical look [13].

2. Literature Review

2.1 Compressive strength of Rat-trap bond

The compressive strength of RTB masonry has been determined by a number of researchers. Its strength has also been compared with English and Flemish bonds using prism testing. Nauman Azhar and Ali Qureshi performed a comparative study on RTB and English bond and concluded that the compressive strength of RTB was 4.6 N/mm^2, 16.4% less than the English bond strength [18]. Jayasinghe [19] studied the comparative performance of English, Flemish, and rat-trap bond. He reported that in terms of compressive strength, Flemish bond is the strongest bond followed by English Bond, while rat-trap bond gives the least strength of all. The strength measured was 2.60 N/mm^2, 2.58 N/mm^2, and 1.38 N/mm^2 for Flemish, English, and rat-trap Bond respectively. Santhakumar et al. [4] determined the average compressive strength of English bond as 1.564 N/mm^2, while that of rat-trap bond was 1.212 N/mm^2. S. Sivaraja et al. [20] found that the compressive strengths of rat-trap bond prisms with mortar ratios of 1:5 and 1:4 are 0.87 MPa and 1.30 MPa respectively. This shows that bricks set-in a richer mortar are almost 49 percent stronger than that in leaner mortar. Medvedev et al. [5] compared different properties of traditional and non-typical bonds and reported that the compressive strength of English, Flemish, and rat-trap bonds are 3.47 N/mm^2, 3.4 N/mm^2, and 3.16 N/mm^2 respectively.

The literature in general shows that the compressive strength of RTB depends on the mortar ratio as well as the compressive strength of the bricks. Richer mortar mix and higher compressive strength of bricks will result in higher compressive strength of RTB masonry. In general, the compressive strength of RTB is 25% less than the conventional English bond. Table 1 presents the summary of the results of various studies carried out for the compressive strength of RTB masonry.

Table 1

Summary of compressive strength of RTB and comparison with English Bond

Refrences	Brick Strength (N/mm^2)	Mortar Ratio	Mortar strength (N/mm^2)	Compressive strength of masonry (N/mm^2)	Reduction from English bond (%)
Santhakumar et al. [4]	5.69	1:3	17.02	1.64	22.5
	4.02	1:3	12.7	0.7	22.5
	8.62	1:3	12.75	1.105	26
Sivaraja et al. [20]	5	1:5	_____	0.87	_____
	5	1:4	_____	1.30	_____
Jayasinghe [19]	_____	1:6	_____	1.38	46.5
Medvedev [5]	_____	_____	_____	3.16	8.9
Azhar and Qureshi [18]	17.8	1:4	16.1	4.6	16.4

2.2 Cost Analysis of Rat-Trap Bond

Cost effectiveness in construction is one of the major demands now a days. Therefore, various studies have been done to compare the cost of RTB with conventional brick masonry. On one side, RTB provides internal cavity to reduce the quantity of material used while on the other hand the brick on edge results in faster construction thereby reducing the labour hours for construction. Sinha et al. conducted a case study and reported that RTB reduces the construction cost about 26.11% [17]. Chaudhary et al. [21] reported that this bond uses approximately 80 bricks against 100 bricks require in English bond for one square meter of wall. Thus saving 20% of bricks in construction. A technical brief developed in Sri Lanka [11] reported that overall cost reduction of rat-trap bond is 26%. A report from Nepal [3] claimed that rat-trap bond reduces the cost of construction by 30 %. Khan and Thaheem [22] reported that RTB reduces the cost by 23% compared to standard brick masonry. Joshi et al. [12] compared the cost for 1 m^3 brick masonry for English and rat-trap bond and found that the later reduces the cost by 57, 20, and 61 percent for cement, fine aggregates and bricks respectively. He also claimed an overall saving of 23% by rat-trap bond in comparison with conventional bond. The pie chart in Fig. 3 represents the material wise cost reduction for RTB masonry. Medvedev et al. [5] reported that labour hours for RTB and English bond are 2.93 h/m^3 and 3.2 h/m^3 respectively. This shows that RTB can reduce the labour cost by 8%.

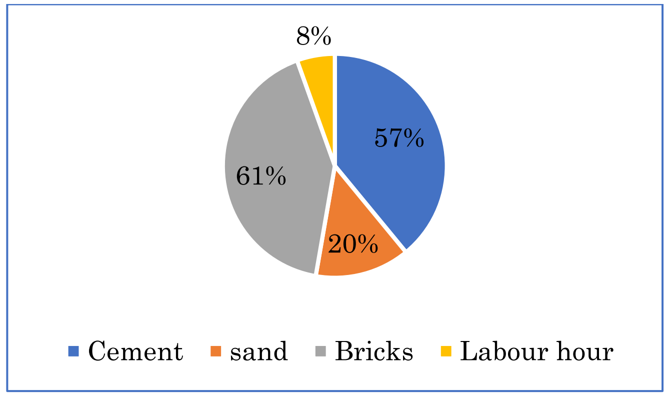


Fig. 3. Material wise cost reduction in RTB Masonry as compared to English bond

The researchers mostly compared the cost of RTB with English bond in terms of material usage and time of work done by the labour. It can be observed that the average cost reduction is about 24%.

2.3 Failure Mechanism of RTB

Limited work has been reported so far on the failure mechanism of RTB. Santhakumar and Sivakumar [4] found experimentally that the weaker zone in the rat-trap bond wall is the rowlock bricks, which fails in shear resulting in separation of the two leaves of the wall. For this purpose, samples having rowlocks with variable strengths were tested and it was observed that the samples having fly ash-lime-Gypsum (FAL-G) bricks as rowlocks has 40 % higher strength than the conventional brick sample. Khan [23] determined that the wall panel of RTB failed in diagonal tension, and the cracks propagate due to more height of vertical mortar joints. Fig. 4 shows the failure patterns of two different bonds, where English bond fails due to sliding at the base and rat-trap bond fails due to diagonal cracks following the path of the mortar joint. Sivaraja [20] studied the out-of-plane failure of box type RTB masonry. They compared the 1/3rd scaled model having roof slab with the model without slab. The latter one did not behave satisfactorily in earthquakes and are most vulnerable to earthquakes.

Based on the studies so far it can be stated that RTB fails in compression mostly due to the failure of rowlock bricks. Similarly, in diagonal compression, the extra height of mortar in the vertical joint governs the cracks propagation.

Fig. 4. Failure Pattern of RTB (left) and English bond (right) [23]

2.4 Thermal Insulation and Energy Efficiency of Rat-Trap Bond

Sustainable and environmental friendly construction is one of the key areas for researchers worldwide. Various techniques have been introduced and further research studies are being conducted. RTB masonry is also one of these techniques. It has been evaluated in terms of thermal insulation, environmental effects, and energy efficiency. Joshi et al. [12] compared the cost and embodied energy of rat-trap brick bond with the conventional brick bond. Experimental results show that rat-trap bond can reduce the embodied energy by 28%. This is equivalent to 13,612 kWh of electricity, 1.17 metric tons of oil saving, 13.6 tons of CO2 released to environment. Jayasinghe [19] measured the hourly indoor temperature of rooms constructed with English, Flemish, and rat-trap bond. It was observed that the rat-trap bond behaves the best in thermal insulation because of the cavity inside it. Khan and Thaheem [22] compared the energy efficiency of rat-trap and English bond masonry. The results are presented in Fig. 5 showing a significant saving in the case of rat-trap bond masonry. Nadarajan and Kirubakaran [24] performed computational fluid dynamics (CFD) analysis on room samples of mud blocks and rat-trap bonded brick walls. The Pattern of air temperature within the houses in both the cases are almost the same. In the case of RTB walls, the air temperature was found lesser inside the house; the average difference was around 0.7°C, while the maximum difference was 6°C. The wall temperature was greater for RTB bonded brick walls by 0.3°C.

It is obvious that the internal cavity provides better thermal insulation compared to conventional English bond masonry. However, research studies also show that the internal temperature of a room built with RTB masonry is 0.7°C less than that of mud masonry.

2.5 Numerical Analysis of Rat-Trap Bond

Santhakumar and Sivakumar [4] carried out comparative computer analyses on rat-trap and English bond masonry and the results are shown in Fig. 6. The graph was plotted up to ultimate loads and it shows that the slope of RTB graph is almost linear up to 60% of the ultimate load. Peak lateral strain for rat-trap bond is relatively higher than the English bond, which shows that RTB is more ductile as compared to English bond.

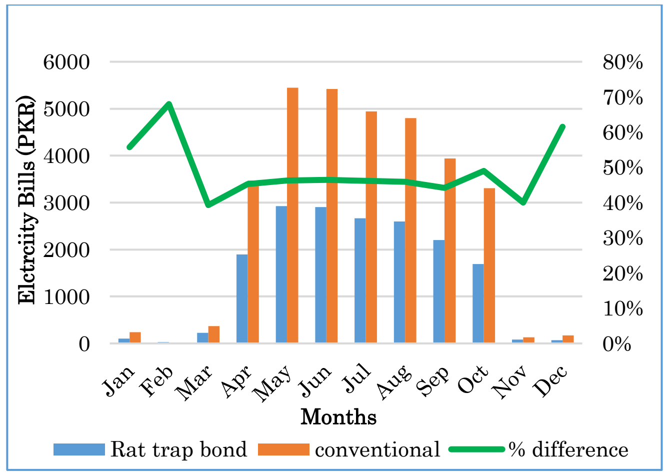


Fig. 5. Electricity cost comparison of rat trap and conventional construction [22]

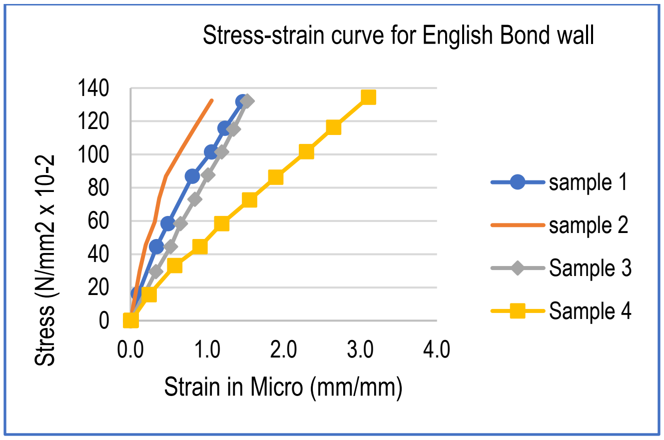
2.6 Behaviour of RTB under Lateral Loads

The study of the behaviour of RTB under lateral load is necessary for its validation against earthquakes and other lateral loads. For this purpose, some in-plane shear tests and base excitation tests on scaled models have been conducted so far which are summarized in this section, however, there is a need to study the behaviour of rat-trap masonry under later loads by conducting quasi-static tests of RTB masonry.

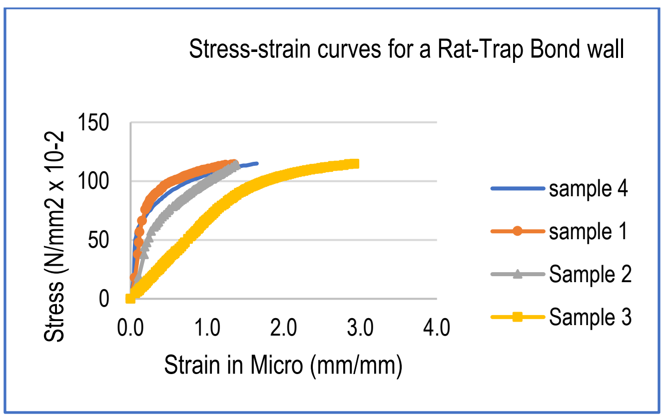
Khan [23] investigated various properties of rat-trap bond (Type-D) in comparison with English bond (Type-A), and bond pattern (Type-B) of reduced thickness (7 inch) in which one brick is laid on the bed while the next one on edge to reduce the cost.

The shear strength of wall panels for brick masonry Type B and D was found to be 13 and 6.5 percent less than that of masonry Type A respectively. The reduction in shear strength for masonry Type B is due to the non-uniform distribution of load on mortar bed. Further, he observed that peak lateral load deflection of type B and

D are 77% and 82% higher than that of English bond as shown in Fig. 7. The lateral stiffness of English bond masonry is smaller as compared to other masonry types. He also concluded that the ultimate lateral load carrying capacity of rat-trap bond is 38% less than the English bond.



(a)



(b)

Fig. 6. Stress-strain curve of (a) English bond (b) and rat-trap masonry [4]

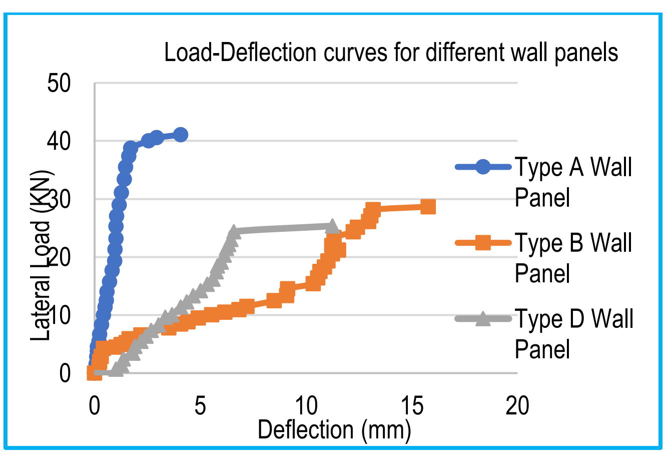


Fig. 7. Load-Deflection for different wall panels at the top [23]

Jayasinghe [19] found that the load-deformation behaviour of Flemish and rat-trap bond was almost the same as shown in Fig. 8.

Santhakumar and Sivakumar [4] developed lateral load-deflection curves along the height of the wall as shown in Fig. 9. The Fig. shows that RTB has larger deflection than English bond for the same load.

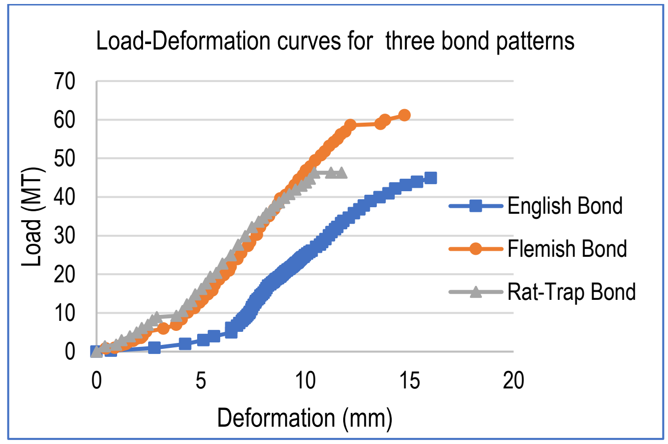
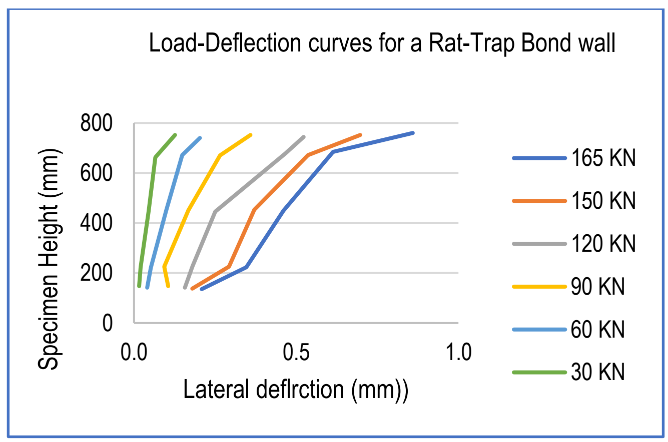
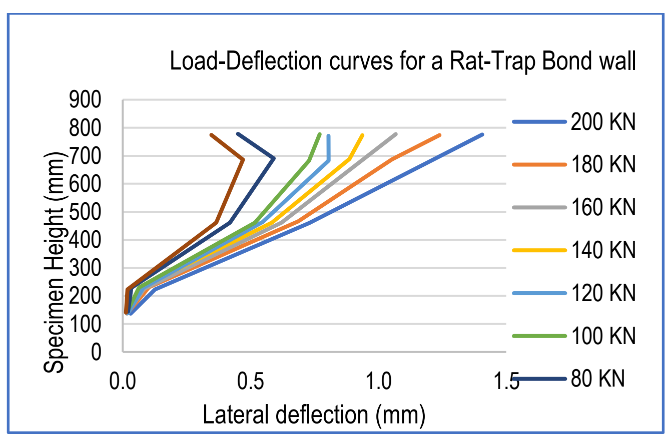


Fig. 8. Load -deflection curves for RTB, Flemish and English bond [19]



(a)



(b)

Fig. 9. Load-deflection curves (a) English bond (b) and RTB [4]

S. Sivaraja et al. [25] investigated the out of plan box type shear behaviour of RTB. They conducted base shock excitation tests on scaled RTB samples repaired with glass fibre reinforced polymer (GFRP), with and without roof slab. The energy capacity, base acceleration, peak modal acceleration, and natural frequency were determined experimentally as well as numerically using the ANSYS package. The numerical values were 18-20 % higher than that of the experimentally determined values. However, the frequency values were in close agreement. A Summary of the results are presented in Table 2.

Table 2

Dynamic characteristics of RTB masonry [26]

Model description	Max impact number	Max energy (Nm)	Base acceleration (m/sec^2)	Peak model acceleration (m/sce^2)
GFRP repair	32	7363.3	7.01	5.98.
With roof slab	21	4069.5	17.40	29.95
Without roof slab	24	3581.58	9.27	30.81

Natural frequency (Hz)

Model without roof slab		Model with roof slab	
Experimental	Numerical	Experimental	Numerical
5.23	5.543	11.02	11.452

The study also concluded that the load deformation curve of RTB is somehow similar to that of Flemish bond. However, the lateral load carrying capacity of RTB is about 38% less than that of English bond. On the other hand, RTB was found to be more ductile as compared to English bond.

2.7 Diagonal Compressive Strength of RTB

Azhar and Qureshi [18] compared the diagonal strength of prism constructed in RTB and English bond. The authors reported that the shear strength of RTB and English bond are 0.59 N/mm^2 and 0.53 N/mm^2, respectively. This shows that the shear strength of RTB is 10.2% higher than that of the English bond. The shear strength mainly depends on the strength of mortar. The RTB prisms were constructed using lime mortar, the lime reacted with the carbon dioxide available in the air and lead to better strength of the mortar. This behaviour was also justified by the triplet testing, where the characteristic initial shear strength was 0.31 N/mm^2 and 0.26 N/mm^2 for cement-lime mortar and cement-sand mortar respectively.

2.8 Recommendations for Future Research

The literature review reveals that the RTB bond has several benefits compared to conventional masonry. Owing to these benefits, RTB is gaining popularity in the construction industry, encouraging the researchers to study its structural performance, stability and to make a clear decision about its use in seismic regions. The performance parameters and mechanical properties reported in the literature are limited and not sufficient for decision making and performance validation. The key parameters like stiffness, energy dissipation, damping, lateral strength, ductility, etc. are either missing or very rarely reported in the available literature. Therefore, it is recommended to study the behaviour of RTB masonry under quasi-static loading and dynamic loading (shake table tests). It is also recommended to study the effect on confinement and reinforcement on the properties of RTB masonry.

3. Summary and Conclusion

Following conclusions can be drawn from the extensive literature review of RTB:

1. RTB was used in Europe till the start of the 20th century for the construction of one and two storey buildings. After being disappeared from the construction industry for decades, Mr. Laurie Baker re-introduced RTB for cost effective construction. The study reveals that currently India, Pakistan, Nepal, Sri Lanka, Russia, and Iraq has constructed various buildings using RTB masonry.

2. The first ever experimental and documented research work on RTB started in 1995 at Anna University Chennai.

3. RTB masonry became part of the National Building Code of India in 2016 which provides guidelines for general construction, materials selection, inspection, precautions, testing methods, and places where RTB can be used. Nepal and Sri Lanka have also developed technical briefs and guides which provide guidelines for construction of RTB buildings.

4. RTB is recognized as Green building technology as it is energy efficient, reduces CO_2 emission, and provides better thermal insulation as well. Compared to English bond, RTB can reduce the embodied energy by 28%. This is equivalent to 13,612 kWh of electricity, 1.17 metric tons of oil saving, 13.6 tons of CO_2 released to the environment.

5. The study reveals that RTB optimizes the cost of construction by 24% compared to English bond. Labour hours for RTB and English bonds are 2.93 h/m^3 and 3.2 h/m^3 respectively.

6. The compressive strength of RTB is 25% less than the English bond masonry. RTB fails in compression mostly due to the failure of rowlock bricks. The stress-strain curve shows linear behaviour for both the bonds up to 60 % of the ultimate load.

7. Peak lateral strain for RTB is higher than that of the English bond, justifying the comparatively high ductile nature of RTB.

8. The shear strength of the wall panel for brick masonry in RTB is 6.5% less than that of English bond masonry.

9. The numerical analysis performed using ANSYS package revealed that energy dissipation, base acceleration, and peak modal acceleration were 18-20% higher than that of the experimentally determined values. However, the frequency values were found to be in closed agreements.

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