Czech Technical University in Prague

Faculty of Civil Engineering

Department of concrete and masonry constructions

Bachelor Thesis

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Czech Technical University in Prague

Faculty of Civil Engineering

Department of concrete and masonry constructions

Dry stack masonry: history, principles and contemporary applications

Bachelor Thesis

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Branch of study: Building structures

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BACHELOR´S THESIS ASSIGNMENT FORM

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III. ASSIGNMENT RECEIPT

I declare that I am obliged to write the Bachelor Thesis on my own, without anyone’s assistance, except for provided consultations. The list of references, other sources and consultants’ names must be stated in the Bachelor Thesis and in referencing I must abide by the CTU methodological manual “How to Write University Final Theses” and the CTU methodological instruction “On the Observation of Ethical Principles in the Preparation of University Final Theses”.

Assignment receipt date   Student’s name

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In Prague on

STATEMENT OF ORIGINAL AUTHORSHIP

The work contained in this thesis has not been previously published or submitted for an award in this or another higher institution. To the best of my knowledge and belief, the thesis does not contain any materials previously published or written by different person except cases where necessary reference is provided.

Abstract

This bachelor diploma thesis is focused on dry masonry structures. It contains overview of historical development, principles of construction and examples of dry masonry systems. The aim is to show beneficial part of the dry stack masonry over conventional masonry, to show applicational principles, types of existing systems and to describe known problems of the dry masonry. In addition to that, STAVSI dry stack system is shown with an example.

Keywords: dry stack, masonry, dry masonry, STAVSI, blocks.

Content

1. Introduction

The worldwide lack of fast constructing systems has stimulated a search for appropriate, easy, fast and cost-effective new ways of wall construction. Among such technologies in rural and fast-growing areas the most promising and perspective systems are masonry and timber. In comparison to timber, artificial stones have less ecological impact and by using dry-stack interlocking bricks/blocks constructors can reach better result for load bearing parts of the house.

By the growth of technologies and industrial development we can assume that in the nearest future there will appear numerous buildings that will form new residential blocks around the cities. With gradually rising demand on quality of thermal and mechanical properties of materials, the producers will have to improve their products and as the progress will not stop, people will strive for better and safer living.

The masonry construction industry has strong need to accelerate processes on construction site, as the most traditional way is labor intensive, slow, because of large amount of mortar joints. Masonry construction meets a range of problems: such as time consumption, or limited number of skilled masons.

As a solution sizes of blocks were increased, that led to reduction of joints and increasing of construction speed. Further need for acceleration of construction process has almost eliminated the thick bed mortar and led to development of non-conventional techniques of masonry construction.

Dry masonry has many benefits in comparison to normal masonry. Despite on similarities: usage of the same principles, schemes of claddings and selection of source materials, mortarless masonry is different by using its own techniques and developed material selection which has nowadays proven benefits. As it is normally exposed to vertical compressive load, dry masonry is not entirely addicted on the bond between the blocks and the mortar in between. The friction between the interlocking blocks of masonry is usually robust to provide a good interconnectivity of the blocks and strength.

Material of bricks differs from natural: clay, sand and water; to artificial compounds such as polymers. This directly affects on the strength of that sort of constructions where their properties have the main and decisive result in material selection and choosing the correct construction layout.

Generally, dry stack walling can be constructed faster with less skilled labour compared to the traditional mortared masonry walls. However, the contact surface unevenness of the blocks affects the constructability of dry stack system and creates additional statical problems for constructors. However the dry stack masonry has its benefits and drawbacks, that should be tested and properly described.

This thesis is aimed at general studying of dry stack masonry. It describes its history, typical problems of the dry stack interlocking blocks and studies about different systems that use the basic principles to construct dry masonry. The main aim is so that this masonry type could be raised with ease and used as fast and effective construction system on the site.

My motivation for writing this topic is the problem of living which exists in both: developing and innovative countries. Lack of construction materials in rural regions, that leads to poor life of people or unreasonably costly buildings made of concrete. In my opinion dry stack masonry can fulfill thermal and mechanical requirements for fast built constructions. Bricks material selection can be adjusted to the local sources of raw material which creates adequate costs. Indeed, engineers look for the most cost effective and accessible construction method, dry masonry offers wide range of benefits, and can be chosen as the primary construction material for less demanding structures.

2. History

Dry stone or dry stack, is a building construction technique by which structures are constructed from stones or blocks absolutely with no mortar to bind them along. As it was mentioned before, by the character of compressive load, dry stack masonry behaviour is not dependent on the bond between the block and the mortar. High pressure on bond surfaces in the block joint creates friction between the interlocking blocks of masonry and it is typically robust to provide high level of connectivity.

Dry stone construction is best notable in the context of stone walls, historically used for the boundaries of fields and churchyards, or on the other hand were used as retaining walls for terracing and supporting soil on the slopes, however such structures as dry stone sculptures, and numerous buildings, bridges, and others also exist.[6]

2.1 History of interlocking bricks

History of dry masonry doesn't have sharp time frame, as it was developing around the Globe in accordance with setting of new eras and human growing. Dry stack masonry dates back to the times of Neolithic Age (10000-3000 BC), the era when growth of stone treatment has been developing, it is also called New Stone era.

Labor efficiency was gradually raising, with the skills of people, who were creating more tools for themselves. People of this era went over to agriculture, with creation of tools for stone treatment. The main stone source were siliceous stones. However, grinding sawing and sharpening of stones gradually allowed people to achieve better quality in stone treatment.

Despite little evidences of the early structures, in countries of Mayo and Ireland related to 3800 BC whole field systems with usage of dry stone walls were found. These may be related to the earliest proofs of dry stack application.

On the other hand, in southern Europe in Greece the cyclopean walls of the acropolis of Mycenae which dated in the latest period of 1350 BC are later, but significant evidence of early examples of dry masonry, which proves that people were actively spreading and studying new types of constructions in different parts of the World.

Indeed, dry stack masonry in the past was the only fast constructed and natural way for building up dwellings and infrastructure objects. In the past some advantageous properties of mortarless masonry were already known, and for instance, seismic behavior was one of the most important for Ancient habitants in South America region.

As it was previously mentioned, historical popularity of dry stack masonry didn't have precise boundaries and time frames. Nevertheless, dry masonry evidences were found across the whole Europe and furthermore in some distant areas such as America and even Australia.

Found stones in different areas result in style for each separately taken region. Stone is costly to manoeuvre, so local and closest field pickings are used as the most convenient, followed by domestically quarried stone. In local regions where only large boulders and stones are located, the walls are affected by increased thickness and appearance is rather jumbled up and chaotic.

In areas where the most common stone is slate (which has layered thin structure and breaks apart easily), you are probably to ascertain fabric pattern of stacking plates of stone diagonally. This sort of wall may be seen the most frequently in Devon and Cornwall. If the slate is more robust that affects regularity and shape of walls, they are more regular, with the flat slate presented in horizontal direction. Usually this is utilized around Lake District. Within the stunning Cotswolds space and parts of Yorkshire the stone is sedimentary rock - limestone, where the golden yellow color of a brand new designed wall ages to a exquisite golden gray color.

Furthermore, as stone appears completely natural in the environment it quickly became a material for human labor. Stone constructions create harmony with nature and are pleasant to behold. Walls, but also smaller buildings and shelters, are built on a human scale and do not stand out in their setting.

2.1.1 Location of historical objects in Europe

As the dry stack masonry has gradually appeared in Europe, not everywhere it has the same name and meaning.

To begin with the historical spreading of dry stack, UK territory has the biggest number of masonry examples which were saved and can be seen now.

For instance in Scotland dry stone boundaries in the fields were called dykes. Dry stone structures were mostly spreaded in the Northern part of Britain and Ireland, where natural stones and rocks exist in soil and on the surface. Region of Connemara in the West of Ireland is full of easy accessible surface rocks.

Dry stone walls have been part of the landscape of the UK for thousands of years. It is estimated that there are over 193,000 km of dry stone field walls in the UK but only 13% of these are in good condition, 17% in an advanced stage of decay and the remaining 70% are derelict. [6]

Figure 1 Drystone dyke at Muchalls Castle, Scotland, 17th century [13]

Figure 2 Galloway dyke on Fetlar, Shetland Islands, UK [14]

Another type of smaller dry stone structures built as signs on the territory of Britain and Switzerland where it was also found are markings or cairns. They were placed on clearly visible positions to indicate mountain paths or the beginning of owned land.

However, in Scotland, where it is called cairns, they were used as a road and mountain top markers.

Figure 3 Dry stone marking or cairn [15]

You may find huge difference in regions of the UK that use completely different designs most suited to the sort of stone or regional techniques transfered from one generation to following. In Scotland they are named 'dry stane dykes' and in Cornwall in the southern west, despite the fact they are made of stone, the walls are named 'Cornish hedges'. Bottom stones are called 'footers', stones that run through the wall known as 'throughs', very small stones to fill the center known as 'heartings' and 'coping' stones to end off the top of the wall.

People used combination of two walls with fillings of earth or sand in between, and the key goal was to avoid draughts. Structures that are dated back to the Iron Age and located in Sweden, England and Ireland are so called turf – roofed blackhouses. Construction presents a double wall of dry masonry with combination of soil with wooden rafters on roof covered with turf with cereal straw or reed. The most significant objects are fortifications in Oland, Sweden “Eketorp Castle”, North Yorkshire “Maiden Castle”, Reeth and Dunlough Castles located on territory of Ireland.

Figure 4 Eketorp Castle, Sweden [16]

Figure 5 Medieval dry stone bridge in Alby, Sweden [17]

Since Medieval Ages, infrastructure constructions were appearing not only in southern parts of Europe but also on the territory of Scandinavia. Dry stone bridge in Alby, Oland, Sweden is a good example of Medieval bridge that could carry traffic from horses and carriages at that time. This is a well preserved double arched bridge, made of limestone.

On the other hand, in Southern Europe terracing and usage of retaining walls can be found in the Mediterranean. Development of dry masonry constructions was supplied by plenty of large stones around. In comparison to hedges, dry stone terracing can resist harsh conditions and are reliable and can withstand for centuries.

In Croatia there exists UNESCO listed dry stone wall "suhozidi". With the objects from Cyprus, France, Italy, Greece, Slovenia and Switzerland these walls were added to the list of the Intangible Cultural Heritage of Humanity.

Such walls were intended for some basic purposes: it clarified the earth for crops, indicated the land boarder, prevented from wind. For example, on the island of Baljenac there exists 23km of dry stone wall.

Figure 6 Dry masonry walls on Croatian island [18]

Figure 7Lion gate of the Mycenae Acropolis, Greece [19]

In the region of Alps, on the border between Italy and Swiss also were found some dry masonry structures, that acted as closings for open spaces under natural boulders and converted it into a functional space for living.

Figure 8Dry stone wall, Bignasco, Switzerland [20]

Figure 9Mosaic embedded in a dry stone wall, Switzerland [21]

In the Central Europe in location around Sumava in Bohemia among fields in the rocks there are also some evidences presented by pastures lined by natural dry stone walls.

They serve as an obstacle for sheeps and show the border of the land. In this area also were discovered dry stone terracing and shed walls with foundations.

2.1.2 Location of historical objects in the Northern and Southern America

As it was previously mentioned, rocky soils are the key factor for existence of dry stack structures. In North America such areas are Pennsylvania, Kentucky and Virginia. These areas are significant by rock fences. This technique was brought from English immigrants to America and from there it expanded to Australia.

Kentucky is one of the most prominent examples of the rich heritage of dry stones in the United States. This region developed using local limestone for construction in large volumes. Dry brick buildings: the mills and dams that leveled the streams, stone dwellings and farm buildings, churches were made of limestone and it was common for Kentucky. Dry stone bridges and embankments of that time until nowadays serve people on daily base. Today, the most widely-recognized known historical constructions made of dry stone are stone walls and stone fences that were serving people as borders in fields and pastures.

Figure 10 Rock fence made of limestone, central Kentucky[22]

Since colonial times, the United States have engineered a huge dry stack heritage. Fields as agriculture roadways and industry developed over two hundred years exploitation of natural stone on a massive scale. For instance, on farms dwelling houses and barns were built. Towns which had own stone court houses, offices, economic institution buildings, religious constructions and shops. Also there were structures for transport infrastructure and industry including drystone mills, dams, bridges, stream and pond borders, moreover such constructions as iron furnaces, lime kilns, and distilleries served people in a good way. Nevertheless, some not mentioned drystone structures still support daily use: we can find drystone retaining walls at stream banks, dry masonry railway piers and embankments, and bridge piers that can be seen among the rest of constructions.

Figure 11Limestone kiln [23]

In Southern America application of dry stone walls as a terracing was one of the way of usage of dry stack technique on territory of Peru in 15th century. If we come to construction of Machu Picchu we will find out ashlar type of construction that the Incas used for their buildings. Ashlar is a perfectly cutted stone, its shape allows to minimize joints between blocks. The Incas were masters on their own and so called Inca architectural style is now well known because of them also.

The Incas were the first who paid attention on seismic stability of the main buildings, particularly on dry cladding. The trait of their constructions was unusually tight and properly done embedding surface of the blocks, in such a way that even now you can't put the blade between blocks. Another feature of the Incas buildings is irregular shape of blocks that were attached together in a way of avoiding critical stresses and unacceptable gaps, and what was more important, irregular shape eliminated lateral stresses during earthquakes, so all masonry kept its stability and position.

Figure 12 Dry ashlar masonry of the Incas, Machu Picchu [24]

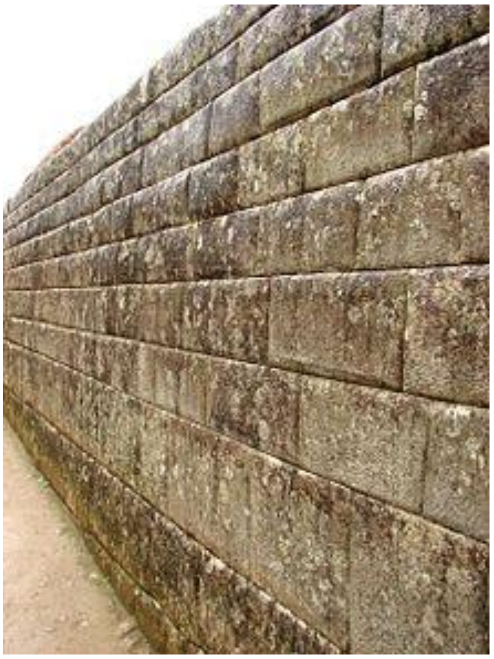


Figure 13Machu Picchu [25]

In general studies dry stone techniques are not restricted by construction segment, in fact, the history of the dry stack knows sculptures, fortifications, bridges that also exist. To serve for particular purposes of the building different techniques and material combinations were used.

2.1.3 Location of historical objects in Africa

In Somalia near Aluula's east lay ruins of ancient platform that played the role of monument. Rectangular in shape 24 by 17m, made of low dry stone on perimeter with rubble inside it is a rare evidence of dry stone masonry in this area. In the corners of rectangle it has massive stones, whereas near the platform edges there are graves, which are outlined in stones.

In Egypt there are prominent objects – pyramids, that were built from 2600 BC. The most famous ones are in Giza

Descending rays of the sun is a symbol that forms pyramid, in addition to that limestone was widely used which has a yellowish shade. Pyramid of Cheops is the biggest and greatest construction of that time with length of 200m and 150 m height it perches above the rest in Egypt.

Figure 14 Giza pyramids, Egypt [26]

Unfortunately in the progress of construction materials, dry stack was pushed away by mortar cladding and next concrete. But still, the most natural and clear way to use dry stones remain retaining walls and terracing. The reasons for such statement are such that when structure of masonry is subjected to lateral earth pressure it works in a vertical direction as a gravity wall, where the weight of stones resists the pressure from soil. Thanks to the friction force in such walls, they behave as monolithic walls, which allows them to keep massive soil and to prevent it from falling. These types of constructions are agricultural terracing and walls that carry paths, roads clean from towering soil.

As it was mentioned before, durability is the greatest trait of dry stone structures, that keep on serving people now.

2.1.4 Location of historical objects in Australia

Over time, historical sites are erased by the development, expansion of roads and disregard for their value, up to their demolition. There is a serious shortage of skilled stonemasons from dry stone, which is aggravated by the lack of accurate guidelines for the restoration and construction of stone structures.

In many places in the world, stones are a characteristic feature of the landscape where the earth was formed as a result of volcanic activity. Ossification of such a landscape is fertile soil, where human ingenuity has cleared harsh stony landscapes from stones for centuries and erected stone structures for specific purposes. Thus, the objectives were to mark the boundaries, define the space with livestock and places for their maintenance, provide housing and serve as a barrier against predators and other animals.

In Australia, dry stone walls were perhaps the first expression of public art in the landscape.

The first stone wall projects in Australia appeared in the mid-1800s in areas where land was cleared for construction. Also on the wall being erected are imprinted owners of land that could give more money with a view to a better aesthetic appearance.

However, this was long before the European settlement. In parts of Australia where there was an abundance of food and stones, the indigenous people of the First Nation engineered low, sometimes round, dry stone structures, some of which were covered with branches and bark, similarly as complicated stone traps for fish and eels; distinctive remnants of which still exist in places like Lake Condah in southwest Victoria and Brewarrin in New South Wales.

Long before the arrival of Captain Cook in 1770, some buildings had already been built in Australia. For example, on the island West Wallabi the Dutch erected dry stone buildings and the French built a garden wall in southern Tasmania.

Despite the myth that most of Australia’s walls were built by convicts teams from Europe were the true builders there. That’s why in Australia there is a plenty of different style objects of dry masonry that have historical and cultural significance.

To present wide range of objects in Australia short list of the most valuable objects was created.

During the pre-European settlement objects that served as fish traps were constructed on the territory of Lake Condah (Victoria), Brewarrina (New South Wales) and also for oysters (West)

On the other hand, during European settlement dry stack can be presented as follow

- Chinese Structures: Daylesford Melton Dam
- Dry stone housing: Yandolt and Walhalla
- Retaining Walls: Walhalla; Cut Hill, Victor Harbor; Great North Road
- Post and wire walls: Melton; Edithburgh
- Dam Walls: Melton; Tod Reservoir, Eyre Peninsula
- Consumption Dykes: Camperdown; New Honiton Road, Edithburgh

Figure 15 Fish traps at Brewarrina [27]

Figure 16 Edithburgh dry masonry wall [9]

Figure 17 Tri spheres, Victoria [9]

One of the objects that goes along the history of dry stack in Australia is Alistair Tune's 'Tri Spheres' in a garden in Camperdown, Victoria, and the retaining walls surrounding them. It was built using Castlemaine slate and has the spheres range in size from 1 to 2 metres in diameter that constructed using old type construction technique called corbelling that formed sphere of stones.

3. Principles of construction and design of the dry stack masonry

Dry stone is the oldest and most proven building technique since Stone era, with its unique benefits. It does not require any heavy equipment for workers and can be successfully done with small capital. Tools for masons are very simple, but constructions are remarkably durable. Some properties that proper wall can obtain are resistance to fire, insects and water, and if design is absolutely correct it can resist earthquake. As for the structure itself, dry stack masonry is aesthetical compliment and enhancement to the landscape.

Study of dry stack masonry or mortarless masonry includes principles of normal masonry and proper bonding rules. This interlocking mechanism is the main point that influences wall stability, levelling of the structure and self-alignment.

Masonry in general comprises two types: conventional and dry masonry. Both have the same bonding principles and comes from the same historical development. Nevertheless there can be selected several differences between them.

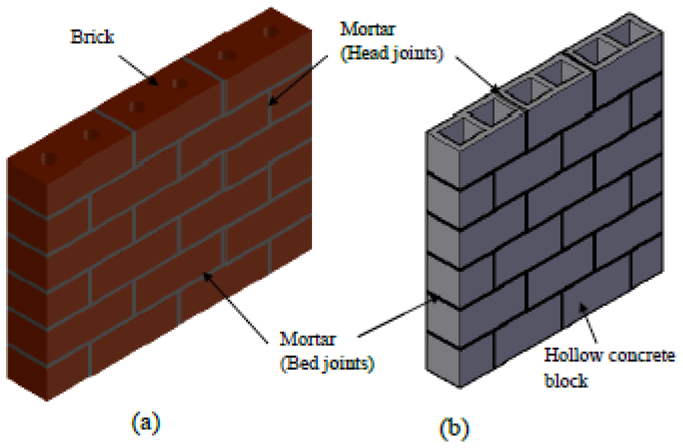
Dry stone structures have many pros over mortared walls. Dry stack masonry relies on the skills of the mason, eliminating the need of numerous skilled workers on a site. It is not necessary to arrange many professional masons, at the time when one the most skilled can control a huge volume of work. Reduced time for the construction to be raised due to lack of water demanding processes on a site. Another point is that dry masonry consider gravity forces and frictional resistance only. Such kind of wall conforms to foundation settlement by providing flexibility of the structure without damage. That saves labor and material expenses by using prepared construction units and faster work.

On the other hand, mortared walls have shorter life span due to presence of mortar joint. There is difference in shrinkage between two joint materials. Frozen rain and snow can get trapped in mortared seams and it will strive to push the joint apart, whereas correctly built dry stone masonry avoids shrinkage and dries naturally without any damage.

3.1 Conventional masonry

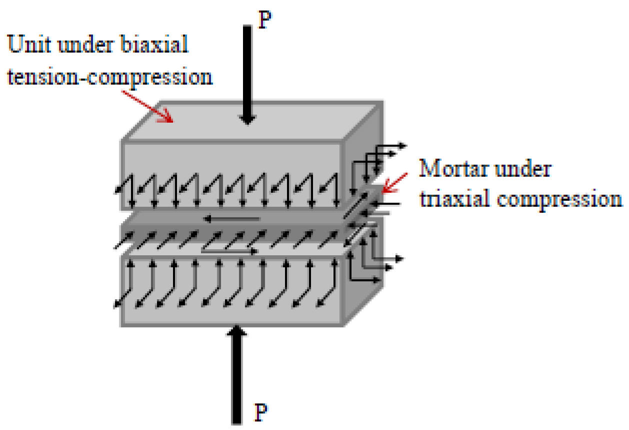
The conventional masonry consists of two units: blocks/bricks or stones and mortar. Widely used material is clay and concrete, the latter can be reinforced with steel or grout to enhance load capacity.

Figure 18 Conventional masonry (a) bricks, (b) concrete blocks [1]



By the character of vertical load, inside masonry internal forces arise. When masonry is subjected to compression, the bond between the mortar and bricks creates a stress state in which the units experience biaxial lateral tension-compression whilst the sandwiched mortared layers are under triaxial compression.

Figure 19 States of stress [1]



The most influencing factors for conventional (mortared) masonry can be listed then

1. Unit strength (f_{uc}): the higher strength of the unit, the higher is the compressive strength of masonry.

2. Mortar strength (f_{mc}): the mortar strength has less influence on the compressive strength of masonry.

3. Mortar joint thickness (t_j): the mortar thickness greatly affects the strength of masonry. With increased thickness the masonry strength decreases and vice versa.

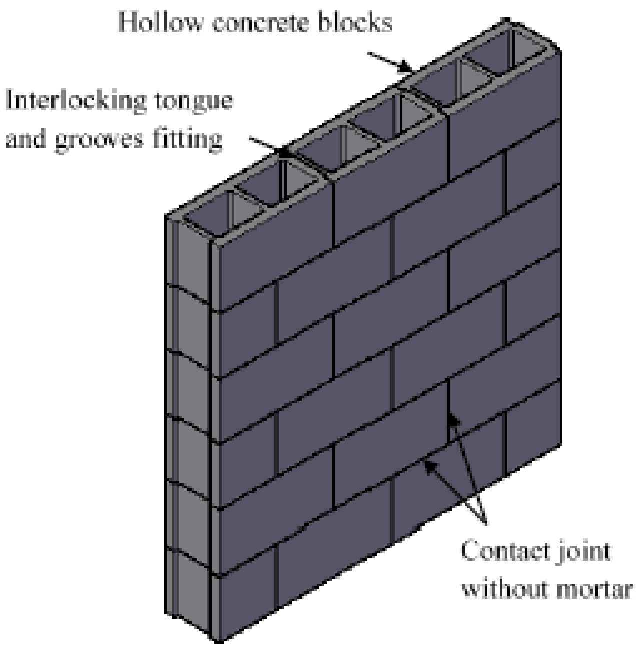
4. Ratio between unit height and joint thickness (H_u/t_j): This ratio influences the compressive strength of masonry; as the ratio increases the strength of masonry increases.

5. Mortar bedding type: The face shell bedding (application of mortar on the face shells only) is shown to decrease the strength in comparison to full bedding (application of mortar on the full contact surface). In spite of this, since mortaring web shells is time consuming, face shell bedded masonry is widely used.

3.2 Dry stack masonry system

It is a mortarless masonry system with blocks that interlocks between each other creating a robust structure. In such a system tongues and grooves can be used to provide levelling and alignment throughout the structure. Dry systems are considered as the least expensive and labor demanding,

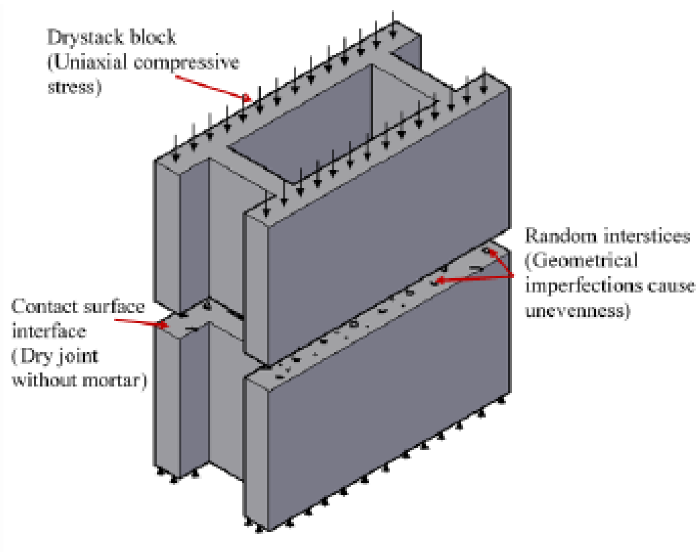
Figure 20 Dry stack masonry [1]



3.2.1 The behaviour of dry stack masonry under compression

In fact, the difference between the character of the load transfer between conventional and dry stack masonry is identical. Dry stack masonry behaviourunder the vertical compressive load is affected by unevenness of the contact surfaces. The contact surface (interface) between the interlocking blocks without mortar and geometric imperfections cause unevenness of the contact surfaces which result in additional internal forces inside the structure. Gaps inside this dry joint can also occur, which may lead to reduction of the bearing capacity and bigger strain. But under the compressive load these gaps are progressively closing. The geometric imperfection and the gap between the blocks are shown in Figure 21.

Figure 21 Dry masonry behaviour scheme [1]

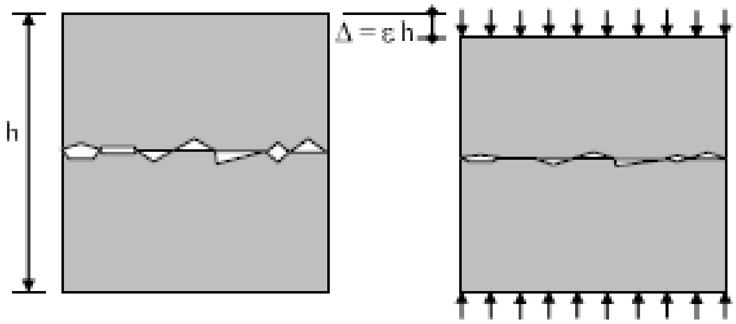


Contact surface unevenness

It is worth mentioning one of the most influencing factor for the dry stack masonry under compression is geometrical imperfection of the bonding surface. It largely affects behaviour of cladding and the strength of the masonry itself.

Picture shows the deformations happened on the joint before and after the load with the carbon paper in between. Existing interstices collapsed reducing the gaps under the compressive load. The strain appeared, it is mainly dependent on the sizes of the gaps on the bonding surface.

Figure 22 Deformation of the bed joint with the load applied. Before (left) and after the load (right) [1]



Ayed et al, (2016) employed a similar strategy of estimating the contact area of dry surface of earthen interlocking blocks using carbon paper impression. Carbon paper impressions were analysed using a MATLAB algorithm. They measured that initially only 20% of the interface area was in contact and with the increase in loads contact area increased to 65% - 75%. [1]

Load eccentricity

Another side of the masonry behaviour under compression is eccentricity. There is a straight dependence between the increase in eccentricity and reduction of bearing capacity. Despite the dry stack masonry can reach more than 30% decrease, the wall can be improved by surface rendering that helps masonry to withstand. Plaster on a wall side plays role of mortar and helps to keep tencile forces.

3.3 Basic types of dry stack masonry

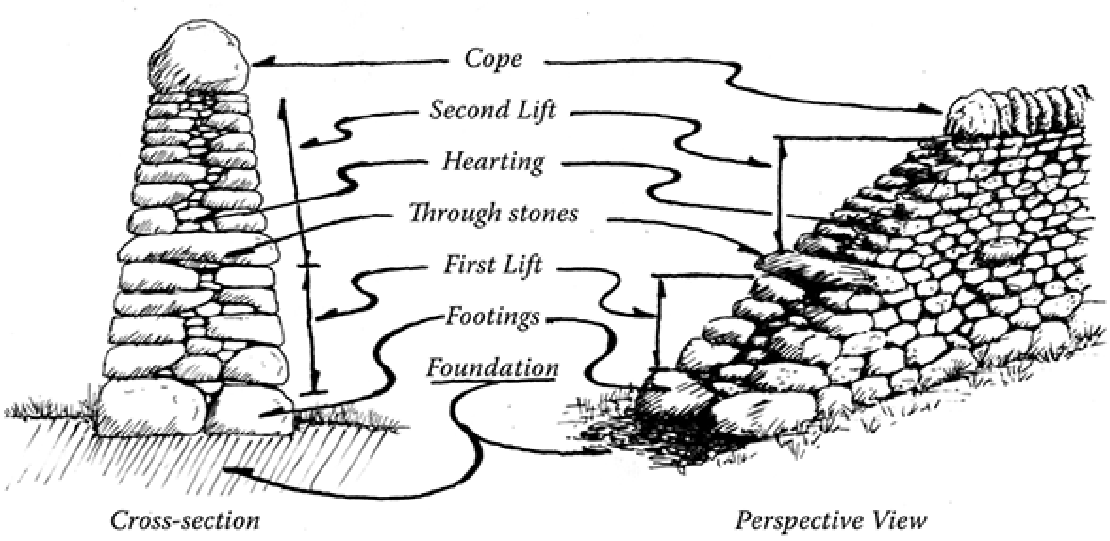
Different types of stone materials will affect on style of the wall and its construction method. As it was mentioned before in the historical development, numerous dry masonry constructions were placed near stone sources, which were boulders or quarried stones nearby. The last option is the most available and affects the later type of wall.

Double wall construction is one of the most accessible types with single block wall construction for dry masonry. Due to its easily construction process, where all stones transfer vertical load to the foundation stones and next to subsoil. Perfect positioning allows to avoid extra forces, and two rows make the system stabil. The system has several traits: diminishing sizes of the stones as the wall rises, flattish stones are used, but in some cases to support rounded stones smaller stones can be used as a chocks.

The structure is layered, and at some intervals courses are bonded by tie-stones between both walls. This bonding increases the strength of the masonry.

Completion of the wall on the top by perched big stones – capstones and smaller stones used as fillings for spaces between beds. The function of capstones is the same as the function of concrete collar, they cover the whole span of masonry, attach the blocks together and prevent wall from breaking apart.

Figure 23 Dry stone wall scheme [28]



Another type of dry masonry construction are boulder walls. That type may have only one side wall that encloses the space under the massive rock. On the bottom part may be seen large flat stones, with tapering to the top by smaller stones. Sometimes capstones can finish the top of the wall.

For instance in UK, there can be seen a nice example of dry masonry - Galloway dykes, which consist of double wall construction at the bottom part with single diminishing wall above. These dykes are located in windy areas, where solid wall can be destroyed by consistent wind load, so dykes appear to be better solution. They have numerous holes and porous structure reduces the risk of the wall unsettling by the wind.

Another famous and widely used type of masonry construction is corbelling. This principle can be selected as one of the most applied and spreaded around.

Corbelling is the principle of overhanging construction, when each consecutive layer of blocks crosses the layer below, which is in fact, planar in section.

It was used since medieval time and served for wide range of constructions such as supports for balconies, arches, ending of masonry walls, etc.

As it can be seen on a section, corbelling structure has two layers: internal construction and outer part which serves as a counterweight and support for internal part. This type of structure played role of a good option for arch construction, but in comparison with true arch that was widely used decades after, corbelling was less efficient in tensile and compressive forces convertation, therefore less stabil.

Figure 24 Spean Praptos stone bridge, 1200 AC, Cambodia [29]

To sum up all the information about the types of dry stone masonry, there can be stated that for every area there can be seen minor changes in construction methods, sometimes reason for that was the limited sources of materials. Different skills of masons and culturals distinctions has also contributed wall appearance.

It also worth mentioning conditions for the wall assembying. As there are plenty of stones, and variety of their positions, a good waller must take time for practical decision and that prolongs time of completion. Today, that leads to shortened number of skilled wallers. Despite the harsh difference in today construction methods, masons remain in demand, due to appreciation of dry stone walls as a heritage.

3.4 Fast implementation of dry stack constructions

Dry stack masonry has two basic principles which play role of objective tasks for masons. The first one, can be described as a requirement for speed of implementation of dry stack masonry construction. This demand can be explained by several principles that represent influences on different sides of masonry related to the speed of construction.

- First of all it is constructability feature, which includes easy construction process that eliminates usage of any corrective measures such as cutting, alignment or another treatment to blocks on a site.
- Second, alignment that influences the smoothness of the work surface. Grooves and straight bonding surface make process easier and does not require any further changes in masonry if it is done correctly.
- Third principle relates to general module coordination, in systems that use that there is a need of proper adjustment of masonry units.
- ext is strict and exact allowances in shape and sizes of constructive blocks that relieves the work process for masons
- And additional principle is standardization of masonry units. Interchangeability of units despite their simple and unique shape makes process simplier and as a result faster.

These requirements allow to reduce need of skilled workers on a site, therefore it rapidly increases construction pace.

Second principle presents requirement for interlocking connections that restrict movements of the dry masonry during and after construction. Tongue and grooves usually fulfill requirements for providing protection against it.

3.5 Main features and problems

While constructing dry stack masonry, there are several factors that mason should consider to avoid failure of the construction. As it comes from the name of the dry masonry construction, it becomes obvious that the main problem occurs between contacting surfaces. All the loads are transferred directly to the basement through the masonry and in addition to bonding surface problem masons have to follow up alignment and bonding principles.

Carefully implemented dry masonry construction has to be vertically and horizontally aligned. All vertical bonding joints are supposed to be strictly in a line along the whole height of the wall, whereas in horizontal plane any mistake will result in smoothness of the wall face. Therefore it comes to a conclusion in vertical alignment accuracy of the wall which varies about 3 percents to the height.

4. Dry stack masonry systems and their assembling

Nowadays, application of dry masonry has developed from constructions of rural houses to medium-sized social and commercial buildings. Despite the lack of standards for design of dry masonry, it does not stop attractiveness of this construction method for engineers. As the growing speed of construction rate was taking place new systems appeared. Although, some techniques were already known there exist some more competitive in the market of dry masonry systems. They have developed recently, during last century with different geometry, dimensions and interlocking characteristics. For instance, Hydraform interlocking system from Africa, Azar and Sparlock in Canada, Haener in USA are among many companies that are currently producing and marketing dry-stacked interlocking systems.

As it was sentenced above, dry stacking reduces the requirement for skilled labor and a costly bonding material like cement and allows to immediately start works for roof and floor construction. It results on the final price of the project, and saves time on a vast scale depending on the system, but generally on the same level.

Most of the hollow blocks are used to replace long and costly process of concrete wall casting. They are mainly made of sand-cement which is competitive with conventional masonry not only in price and quality, but in strength as well.

For example, the Sparlock system and Haener system use material mix ratios of cement to sand/aggregates as follows. The ratio is more than 1:10 to fulfill requirements for strength of the thin block webs and to withstand pressure. In Africa and Asia blocks are mainly made of stabilized soil due to low price demand of the housing.

4.1 THAI interlock brick system

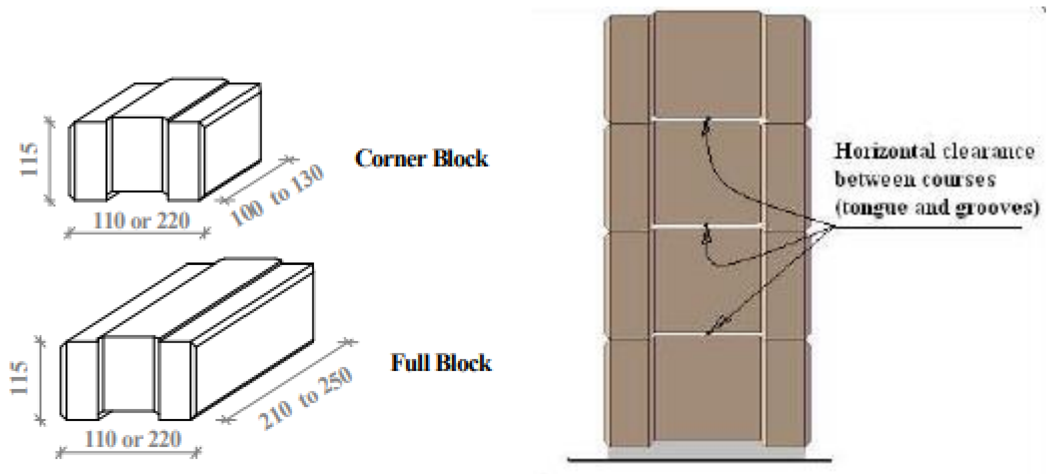
The system uses blocks of 300 x 150 x 100mm with grooves on a sides that create full height render key on a façade. Inside the block there are holes that reduces weight and can be used for reinforcement or communication conduits. These grooves reduce overall strength of the masonry and they can be used for grouting or reinforcement if needed. The strength of the masonry made of Thai blocks then would depend on surface render, or grout and reinforcement inside the holes.

Figure 25 THAI interlock system [3]

4.2 Hydraform interlocking system

Hydraform interlocking blocks are made of mixture of soil and cement which makes the system competitive among others. This is very cost effective system because compound of the mixture is soil – the most abundant construction material. Cement is presented in the mixture in amount of 5-10%.

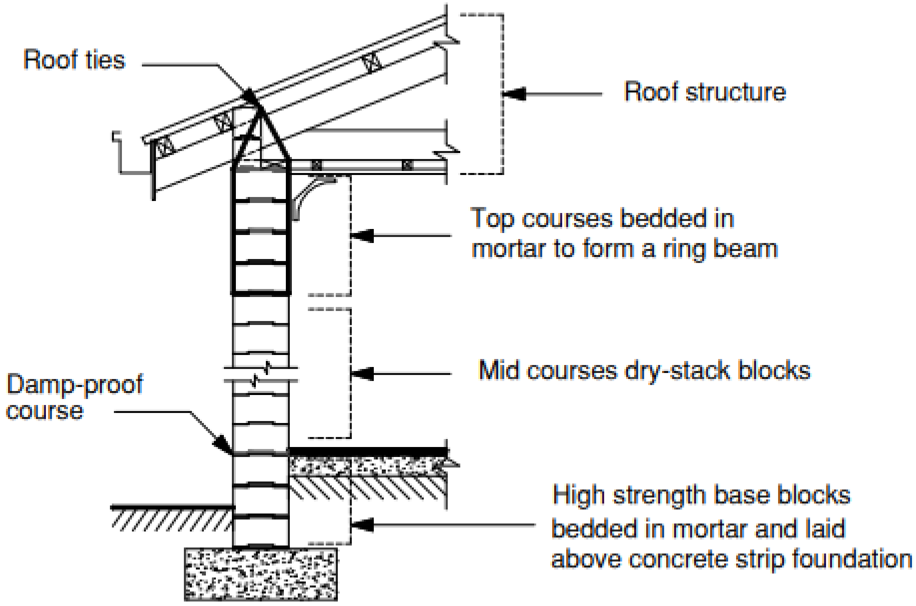
Figure 26 Hydraform blocks [3]



As it allows movements along horizontal joints it also offers tighter vertical joint.

This block is massive and does not have any holes inside which results in stability effect achieved not by locking principle but by massiveness of the construction.

Figure 27 Hydraform construction [4]



4.3 Solbrick system

Another solid brick example of interlocking system also comes from Africa, with dimensions 250 x 200 x 100mm it provides small horizontal cavities between the courses. Sides of the bricks are different which eliminates wrong usage and unnecessary rotation during the construction. Although, Solbrick system seems to be easy in use, it does not suppose construction of partitions or internal walls.

Figure 28 Solbric interlocking brick [3]

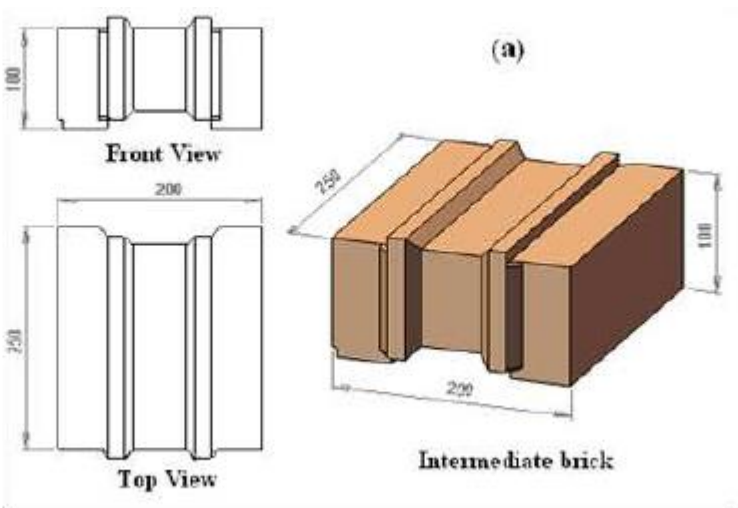
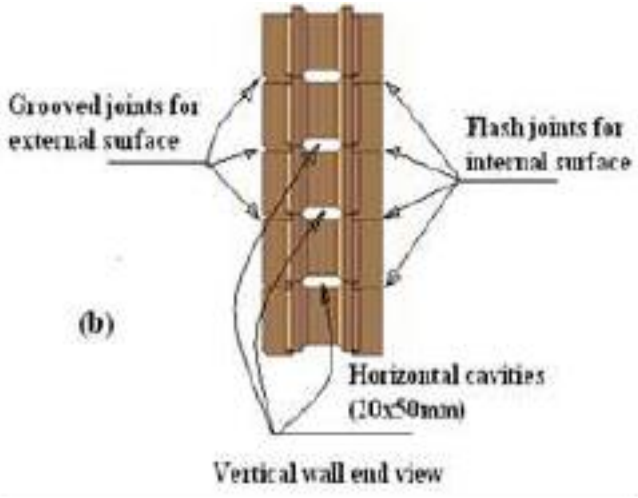


Figure 29 Side view with cavities in Solbric wall [3]

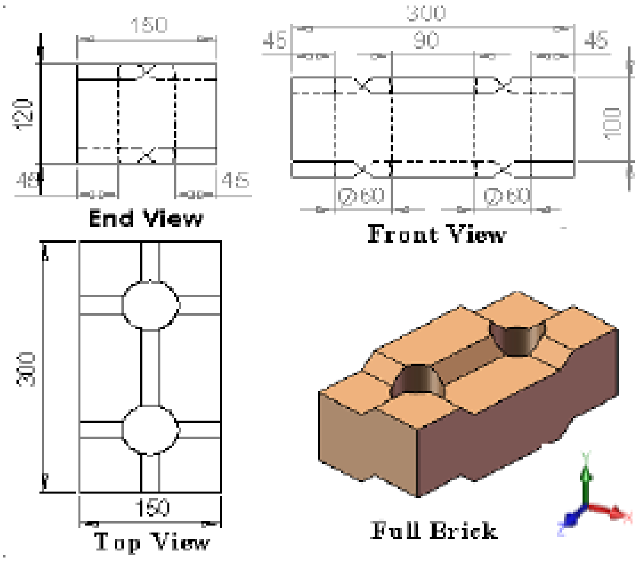


4.4 Bamba system

This system is the next example that comes from South Africa, where demand on fast constructing building led to appearance of multiple dry stack systems.

Bamba system presents perforated hollowed brick. The shape of brick does not have grooves, but it is done by principle of osteomorphic brick with protrusions and depressions that allow to keep tensile forces arised in the masonry.

Figure 30 Bamba brick [3]



Bamba brick provides better accuracy of the cladding over the rest types due to its shape and easy construction process, but production of the brick requires fulfillment of several factors. This accuracy depends on proper soil selection and mixture ration, therefore the system is not perfectly suit for developing countries as production needs accurate machinery and high skills in soil selection, especially in case of different soil consistency in regions. Moreover the system productivity depends on bricks accuracy and existing defects that complicates the process.

Despite all the differences between systems, to describe properties of the masonry compressive strength parameter is used. This can be achieved only by testing of the specimens, however there is still no established procedure of the dry masonry calculation, by known properties designers can assume behavior of the construction.

5. Contemporary examples of dry stack masonry in Czechia

Practice of dry stack distinguishes several methods of buildings construction using the dry masonry principle, or respectively the principle of gluing the construction elements only in a single plane taking advantage of rectangular grooves located in the opposite side faces of construction elements. These grooves serve as guides for precise connection of two neighbouring blocks in the wall body and they are designed to break the direct side face joint line at neighbouring blocks.

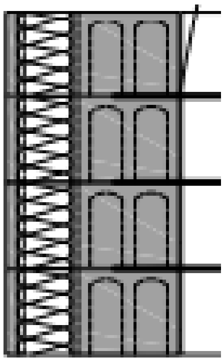
One of the buildings construction methods is represented by a group of construction blocks featuring a sandwich-type arrangement of multiple materials firmly bound in a single unit. As an example of such design the complete building system for shell constructions by the company Betonové stavby – Group s.r.o. can be mentioned.

The company uses Livetherm blocks which consist of thermally insulating blocks of internal supporting and non-supporting walls, form parts and ceiling structures. Sidewall panels are formed by liapor concrete sandwich blocks designed for single-layer enclosing and backing masonry. The tongue-and-groove system is implemented only in the side faces and is not self-locking in the wall body, therefore it ensures that the blocks are bound in single axis only. This system does not eliminate the need to use mortar for coursing joints during walling as such.

Figure 31Livetherm block assembying [30]

Figure 32 Livetherm block system in the corner [30]

Figure 33 Livetherm block system in section [30]



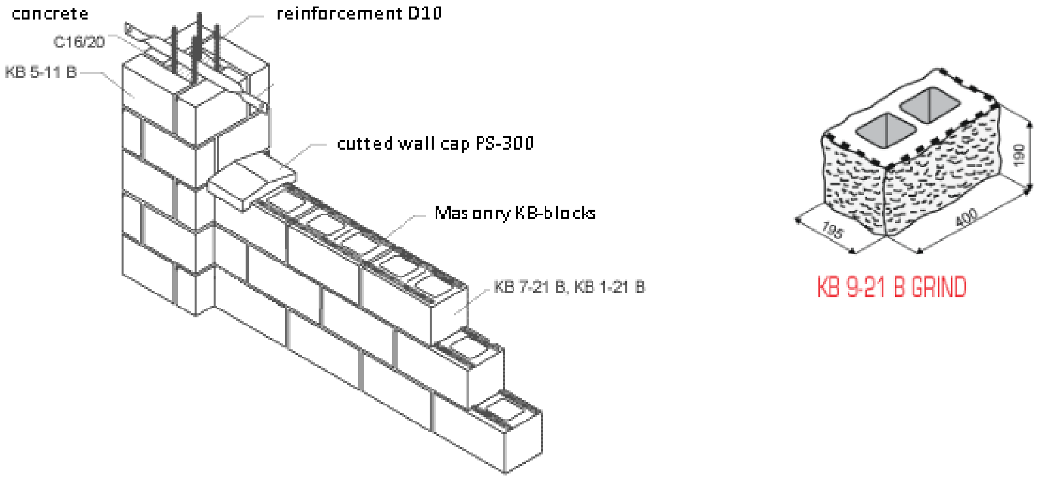
Pairing of Livetherm blocks is done manually or using the grout. Machine pairing has more effective result and Maxit MUR 983 or Weber Color Klinker grout are recommended for that.

Figure 35 Machine pairing of blocks [30]

Figure 34 Manual pairing of blocks [30]

Another type of block using some aspects of dry masonry – KB Blok – has pressed - in groove in the longitudinal axis of the block on its upper face. A tongue in the longitudinal axis of the block on its bottom face fits in this groove. This design of blocks does not allow for universal orientation of blocks in the upper layer in the wall against blocks laid in the lower layer. These blocks solve neither interconnection of separating walls, nor installation of infrastructure. If the extension on one block breaks, the consistency of the whole wall is compromised.

Figure 36 Example of the wall KB blocks [31]



5.1 Stavsi system

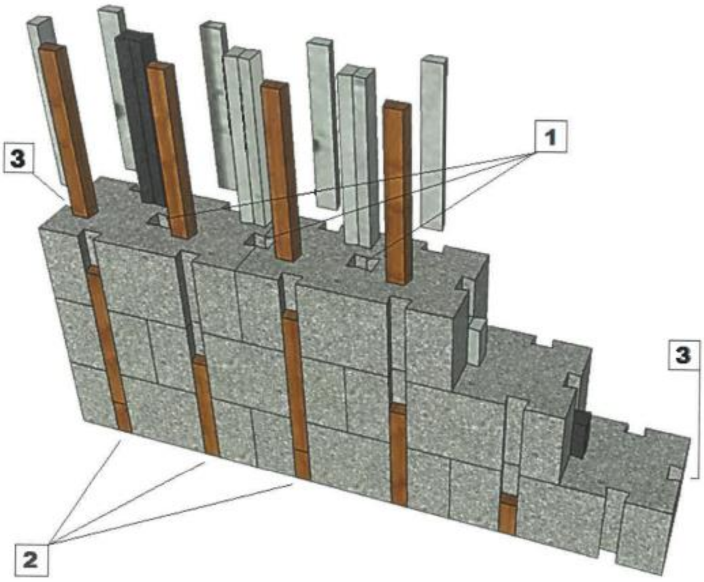
The system is a patent technology located in the Czech Republic.

That technology implies dry masonry technique as a basic technology that is suitable for engineers and easy for understanding. Precise dimensions of the blocks exclude use of glue or any kind of mortar which makes the system clearly dry.

The system is based on the technology of bonding the blocks, which are fixed to the bonding elements, by means of vertical rails that allows the structure to remain stable.

This technology uses the principle of vertical segment pillars connecting adjacent blocks through a large number of self-locking joints. Vertical segment pillars are located on both the outer sides of the wall and inside the wall that prevents any block deflection of the wall both in the vertical and in the horizontal plane through the block bond. Such reinforcement essentially constitutes reinforced masonry in each segment of the wall structure, with all the associated advantages, particularly high rigidity and toughness at the same time.

Figure 37 Example of STAVSI wall. Notations 1) Internal joint between blocks; 2) Connection of blocks from the wall side, with using segment pillars of different height; 3) Side joint [2]



The STAVSI wall without bonding the blocks together with a network of expansion joints effectively eliminates the effects of wall deformation, thereby reducing cracks, bulging or twisting. The frequency of the micro-joints in the wall body, together with the interaction of the blocks and connecting strips, makes it possible to effectively resist any building movements.

Material

The STAVSI block is manufactured from Liaporbeton (lightweight expanded concrete). The connecting rails are made of wood, reinforced concrete and formed recycled rubber reinforcemed with steel. The wooden rods are mainly intended for walls in the interior of the building, while the reinforced concrete are used in the exterior and in the internal grooves of the blocks.

5.1.1 Constructive elements

STAVSI is designed for buildings with rectangular or linear plan. Therefore construction takes place exactly according to the project. For the start project derives the number of blocks needed to build the building. And STAVSI blocks can be combined with any other materials. At the time with readiness of the floor, partitions are built alongside the other walls within the floor that accomplishes the level structure.

Generally the system is presented by four basic types of blocks that may be vertically connected by two types of connecting rods.

Blocks are exactly shaped and precisely dimensioned. They can be divided into two groups: external load bearing blocks and blocks for partitions. Their strict dimensions cause restrictions for the sizes of construction which has to be easily divided by length of the block – 250 mm. As for height it must contain blocks of 200 mm.

As it was previously mentioned, material for blocks is Liaporbeton - a lightweight concrete with ceramsite which was vibrated and formed a perfectly cutted blocks with high thermal and acoustic properties.

There exists two classes of strength for external load bearing walls which are noted as L10, L20 and second, with increased strength L12, L22. The main difference between them is compression strength 6 MPa and 12 MPa respectively. It comes from the different density of the source mixture: 920 kg/m^3 against 1200 kg/m^3. For internal wall types L30, L40 are used.

The height of the blocks is standardized to 200mm, while length can vary between 250 mm and 500 mm.

Table 1 Mechanical properties of the STAVSI units

Compression strength	6-12	Mpa
Thermal conductivity	0,23-0,31	W*m^{-1}*K^{-1}
Sound insulation Rw	42	dB
Fire resistance class	A1	

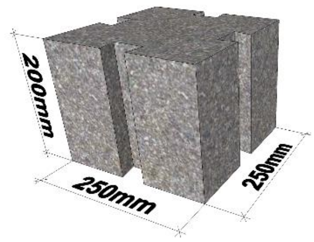


Figure 38 L10 external block [2]

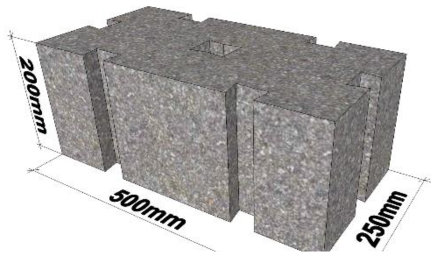


Figure 40 L20 External block [2]

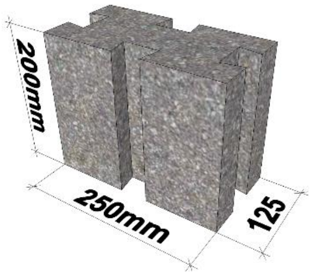


Figure 39 L30 internal block [2]

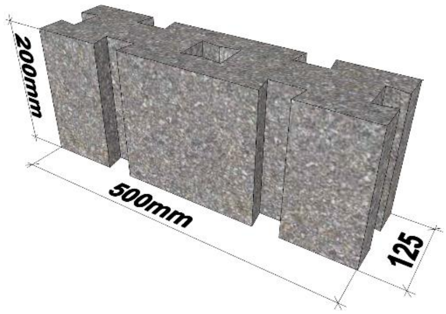


Figure 41 L40 internal block [2]

Connecting rails

The basic unit of any STAVSI building material is the building set. Each building set consists of a calibrated block and connecting rails that will fix it to the surrounding sets in the wall. The connecting rails form an auxiliary connecting material.

There are two basic types of connecting rails

The inner connecting rails are used to insert and fasten the blocks in a central groove with a double dovetail shape (two isosceles trapezoids connected by a shorter parallel side).

The outer connecting strips are used to insert and fasten the blocks in the outer grooves on the wall surface with a dovetail shape.

Inserting the connecting strip into the corresponding slot creates a self-locking connection. The inner and outer connecting rails are manufactured in basic lengths of 400 mm. Rubber and wooden connecting rails are also produced in lengths of 100 mm and 300 mm. Connecting strips with a length of 100 mm and 300 mm must alternately be used to place the walls and at their termination points. Although, in exceptional cases, 200 mm connecting rails are used. If necessary, the shorter rails are made of 400 mm rails as needed directly on site using a hand saw and a power cutter.

Table 2 Types of connecting rails

Extruded recycled rubber with RF steel	100, 300, 400 mm only for inner connecting joint as it eliminates tensile stress in mortar
Soft or hard wood	100, 300, 400 mm internal connecting joint
RF concrete with D 4 or 8 mm	400 mm only for outer connection joint

Figure 42 Dovetail shape of rails

Figure 43 Rubber rails

Connecting rails are used for vertical connection of vertically and horizontally connected blocks within the built wall. The connecting strips ensure a firm connection of the blocks and guarantee automatic perpendicularity and flatness of the walls being constructed. The inner joining strips may exist as separate products (their cross-section forms a double dovetail) or may be formed by using two oppositely aligned outer joining strips (each with a dovetail-isosceles trapezoid cross section) of the same material.

For each block, there are a number of material combinations of inner and outer connecting rails. The choice of a particular combination of connecting rail materials is based on the specific requirements of the building.

5.1.2 Construction process

The main condition for correct construction is respecting the dimensions of the STAVSI blocks. The height of the walls is given by an integer multiple of the height of the blocks (X x 200 mm), the length of the walls is given by an integer multiple of the base block STAVSI (X x 250 mm) and the width of the walls is given by an integer multiple of the width of the blocks STAVSI (X x 250 mm).

Construction process starts from foundation, where different type can be applied. We will consider the existing site object near Beroun with foundation slab.

In order to eliminate unevenness of the foundation slab, the first series of STAVSI blocks is based on mortar (M5 type mortar) or concrete bed of approx. 5 mm thickness on the waterproofing strip. Then assembling of blocks starts.

First, the corner blocks settle and align to the same height and right angles.

Figure 44 Setting of the corner block

Figure 45 First course laid on mortar

The strings are used to determine the edges of future walls between the corner blocks and further blocks deposited on the mortar. The plane on the blocks' loading surfaces and the right wall angles should be carefully checked. Positioning of the blocks should be properly adjusted with the edge.

Next, partitions are connected perpendicularly to the grooves of the supporting walls. They are attached to the load-bearing walls either at the points of the outer vertical grooves or at the side joint of the supporting blocks.

Then connecting rubber rails are placed into the internal grooves with length 100 mm. To every second outer groove 100 mm connecting rail is inserted after.

Figure 47 Position of the connection rails [2]

Figure 46 The entire process of wall assemblying [2]

The same principle for laying of the blocks starting from the corner will be kept, that will create a proper wall structure. As for rails, places with 100 mm will be covered by 300 mm rail in the next row, that process allows to keep the walls stable.

All walls must be constructed simultaneously, course by course, but while masons are keeping proper construction principles the can do work independently starting from different positions.

The STAVSI building system is based on dry assembly of individual parts. Therefore, it is preferable to use another dry assembled technologies and techniques (gypsum board, OSB, etc.) in the project.

The electricity, water and heating distribution project should preferably use vertical external grooves for vertical distribution. It is advantageous to project all horizontal distribution systems into floors or ceilings.

Figure 49 Hollow slab opening for communications

Figure 48 Wall construction with concrete lintel

As a rule, the building openings for windows and doors are given by an integer multiple of the STAVSI base block (X x 250 mm). In justified cases, holes X x 125 mm wide can be used.

5.1.3 Advantages of the STAVSI system

As the main benefits of the STAVSI system there can be selected several points.

- Simplicity – the system is very easy for constructing and doesn't require special skills, it is enough to have only 1 skilled mason on a site to control the process. As it is a dry masonry - nothing concerning water is involved.
- Precision – right shape of blocks and proper placing with vertical rails provides exact project fulfillment. It also allows to cut expenses as no additional block cut is required
- Speed – Productivity is twice higher than conventional building systems; worker builds up 2,5 m^2 of masonry per hour.
- The system is environmentally friendly and supports the modern principles of sustainable construction. It may fully meet requirements for low-energy building. In case of disposal of the building, all parts can be recycled and reused.

5.2 Example of the STAVSI construction

In the attachment to the thesis there is an example of design and calculation done with STAVSI dry masonry system.

The building presents one storey masonry construction with flat roof done by hollow slabs. The prefabricated hollow slabs that are used in the project provided by GOLDBECK company. Structural system of the building consists of transversal load bearing walls made of L10, L20 class of STAVSI blocks with load bearing capacity 6 MPa.

Provided calculations are aimed to show general ability of the used block system to carry load and to prove effectiveness of this design selection for particular construction.

In the data for the calculations were used blocks 500 x 250 x 200 mm with density 920 kg/m^3.

And it was shown based on Eurocode 6: Strength of brick and following masonry strength. But with the lack of standards for dry stack masonry, in the calculations was used thin mortar parameter, which limits thickness of the mortar up to 3 mm. Then design strength of the masonry was evaluated, from which required area of the footing of the wall was obtained.

By the calculation it seems that used system has proved its properties, by being sufficient in design conditions and therefore by further benefits that the system will bring to the construction process.

6. Conclusion

In this thesis the general information about drystack masonry was covered. Several main points were mentioned to prove the ability of the dry masonry to compete with another conventional systems, such as material expenses, labour efficiency and design characteristics. Dry stack masonry is beneficial due to its construction effectiveness and small labor demand.

The thesis also shows how to approach the design procedure, using Eurocode, especially for me it was a new experience, when I used unstated in the Eurocode design procedure and adjusted calculation to the existing standards.

As the system still do not have legal procedures and by the standards designers use definition of masonry as blocks tighed with mortar. Despite range of problems that mortar covers in the joints and height alignment it requires skilled masons and time. In contrast to conventional masonry, mortarless cladding would require precision in the units production but faster implementation and small cost are advantages that set engineer's mind to choose dry masonry in some designs.

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List of attachments

- Design of the masonry system STAVSI, Calculations
- GOLDBECK prefabricated slab. List of specification
- Drawing: Plan 1:75, 1:10