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Characteristics of a robot oriented building block system

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Abstract. The application of that robot system for the automatic assembly of commercial cavity blocks is the subject of the following report.What is characteristic of cavity blocks is the fact that they are at first assembled dry, without cementing material, and the masonry is later filled with mortar. As to their weight and dimension, the cavity blocks used by various companies are adjusted to the ergonomics of a mason. The entirely different characteristics and abilities of assembly robots are not taken into consideration. However, their dimensional tolerance is relatively small (0.5 mm). Furthermore as cavity bricks, they have conic and oval recesses. Both features are strongly favourable for automation.

This report will highlight specific problems during automized construction assembly with commercial standard assembly elements, and help to solve them[6].

1. Characteristics of a building system

The basic forms of construction systems for the manufacturing of building parts result from the type, dimension, material, quantity and location of the respective building part and its components. Each of these building systems is associated with a certain operating procedure; such procedures are generally characterized by a working object, working instruments and working methods. The search for conceptual varieties [16] of automized systems for the erection of building parts leads to a three-dimensional solution field for partial functions, which is made up of the variations of 1. the working objects, i.e. the building parts to be erected, 2. the working instrument, i.e. the tools and materials used and 3. working methods, i.e. the operating procedure employed.

Working object. As to the working object, building construction differentiates between the following building parts: 1. unitized units, 2. supporting walls, 3. storey ceilings, 4. girders and 5. columns. The criteria which influence the arrangement of assembly elements and thus their mode of connection are shown in fig. 1.

supporting and nonsupporting	columns, girders, supporting exterior walls, supporting and non-supporting interior walls
insulating and dividing	sound-absorbing, heat-insulating, water-resisting
geometrical dimension	one-dimensional (e.g. struts, columns, girders), two-dimensional (e.g. wall panels), three-dimensional (e.g. unitized units)

Fig.1. Criteria relevant for the automation of a building division

Working instruments. Working instruments include any tools and basic materials used (fig.2).

materials	unitized units, blocks, columns, girders, mortar, etc.
auxiliary constructions	Units of conveyance, auxiliary materials, structural frameworks, mortar pumps, gauge systems, etc.
tools	robots, manipulators, cranes, etc.

Fig.2. Classification of working instruments

Working methods. The operating procedures discussed here are used in the construction of vertical building parts in building constructions, i.e. the building parts must either be constructed vertically from the beginning or at least be brought into a vertical position afterwards. Building methods for the construction of building parts can be distinguished as follows: 1. assembly construction method, 2. skeleton construction method, 3. panel construction method, 4. room-unit construction method, 5. casting, 6. foaming and 7. concrete cavity construction.

For reasons of acceptance, feasibiliy and propagation, only those building methods which predominantly use solid building elements are analyzed and employed for the development of operating procedures suitable for automation. Therefore, the emphasis of these investigations is on the assembly construction method [6], [10].

2. Characteristics of building assembly systems

Discreet, separate assembly elements. What is characteristic of construction assembly systems is the fact that building parts are erected in the assembly method, i.e. they are put together by means of discreet, solid assembly elements, which can be of a very different complexity (fig.7). For example, this assembly method is opposed to the concrete cavity construction, which is related to cast.

Assembly jointing technique. The assembly system is determined by the jointing technique. It is appropriate to differentiate between the relevant jointing types of the assembly construction method, namely those which have already been used in the building sector or are feasible there (fig.3).

geometrically positive joints	screwed joints, spring locks
force-connected joints	compression joints
compositions of matter	welding joints, bonding joints (incl. mortar)

Fig. 3. Jointing types

Those joints used with cavity blocks form a combination of different jointing types. Depending on the individual manufacturers, this method of concrete cavity construction is combined with geometrically-positive cavity blocks [10], [20], [21].

3. Reference system - who defines the absolute position?

The basis of every measuring and tolerance system is a suitable reference system. With it, the zero position of a three-dimensional coordinate system can be defined. The absolute position of assembly elements can only be determined, if a zero position has been defined beforehand.

The relative position of the elements towards each other can also be determined without an absolute reference system. However, the individual measuring errors add up, which renders a reproduction of the result impossible.

If the assembly system consists of a handling system (assembly robot), the building parts and assembly elements already constructed (pallet, point of transfer of a depalletizing unit, etc.), basically any partial system may serve as a reference system (fig.4).

Besides the partial systems, any other geometric fixed point may also serve as a zero position of a thus defined reference system. Then, however, the relative position of *all* three partial systems to this additional fixed point must be determined.

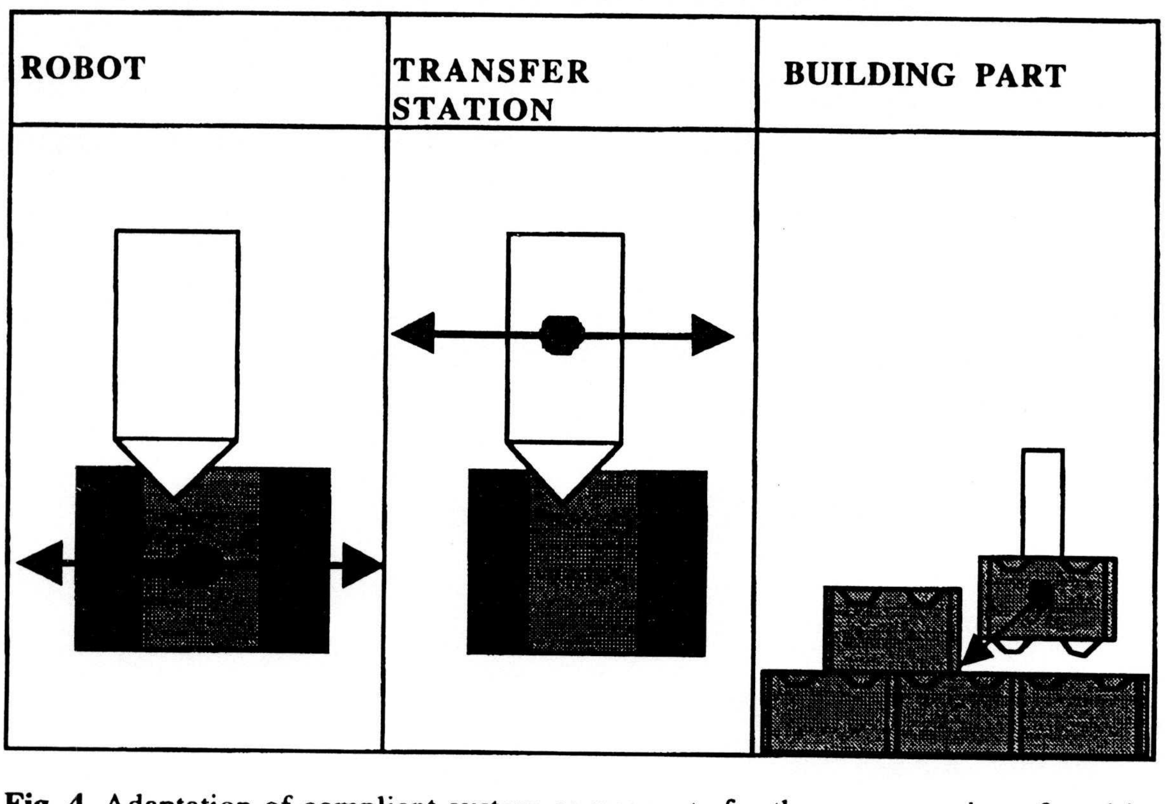


Fig. 4. Adaptation of compliant system components for the compensation of position errors in the different reference systems

Robot as reference system. For the construction of a building expansion B, it is feasible to use a robot system as a reference system which itself used a previously constructed building part A as a reference point. This solution is particularly suitable in the case of automatic cranes which dominate the construction site (e.g. SMART [2]). In such firmly-installed robot systems, their internal position sensor system can be used. A mobile robot needs additional elaborate navigation systems to carry out the same task (fig.4).

Building part as reference system. It is also feasible to construct a foundation manually or to level out a first layer of bricks prior to an automized construction assembly. The robot system is subsequently adjusted in accordance with this reference system. The absolute position of the assembly elements on the pallet is also defined by its relative distance from the constructed building part. This method is particularly appropriate, whenever a mobile robot (see above) or a small, firmly-installed robot within a building is used (fig.4).

Transfer station as reference system. For the construction of a building expansion B it is also possible to use a transfer station of the conveyance of assembly elements as a reference system which itself used a previously erected building part A as a reference point (fig.4)

3.1 Consequences for the assemply process

For the two most important tasks in the assembly process, namely "depalletizing" and "jointing", the consequences listed in fig.5 result from the definition of the reference sytem.

REFERENCE	JOINTING	DEPALLETIZING
Robot	In the assembly process, the positioning of the blocks is exclusively determined by the robot. A direct control of the relative postion of the assembly elements to one another does *not* take place.	The block adjusts to the robot system. This adjustment can be forced by a compliant gripper or a compliant block. (see Fig. 4)
Building	In this case, the block adjusts to the previously-constructed building part. This adjustment can be forced by a compliant gripper/block system or relative positioning and non-bonded jointing (see chapt. 8). In the second case, the robot must trace the relative error (joint width) by sensor (see fig. 4).	In this case, the depalletizing process can only be launched, if either the robot and the transfer station (pallet) are situated in an exactly-known relative position to this building part or if the robot system is equipped with corresponding sensors (e.g. camera system) for the detection of the palletized blocks.
Transfer station	The positioning of the blocks depends on the transfer station. Therefore, the transfer station itself must use an exact reference point prior to the assembly process, e.g. a different building part. Commercial pallets, for example are not suitable (see chapt.7).	Led by sensors, the robot adjusts to the layer of bricks. It memorizes this initial position and places the block in accordance with this zero postion (see fig. 4).

Fig.5. Consequences of reference systems for "jointing" and "depalletizing".

For the reasons mentioned in the previous chapter, the following valuations for the different reference systems result (fig.6):

Reference system	Absolute positioning	Relative positioning	Non-bonded joining
Robot	+ +	-	-
Building	- -	+ +	+ +
Transfer station	+	- -	- -

Fig. 6. Suitability of the reference systems for different assembly methods (Explanation of valuations: ++ very favourable, + favourable, 0 neutral, - unfavourable, -- very unfavourable)

4. Assembly elements

4.1 Common construction materials

Construction materials for assembly construction with industrial prefabrication which can be used for an operation process suitable for automation [11] .

The complexity of building parts to be erected is determined by the degree of prefabrication. Thus, wall elements can already be equipped with windows, shutters, etc. Unitized room-units can be equipped even more completely.

4.2 Requirements of assembly elements suitable for automation

Clarity. Compliant joints which are self-adjusting and tolerant as to errors lower the claims to the accuracy of assembly elements (blocks, bricks), however cannot replace their definition. Every automized assembly requires geometrically-defined assembly elements, for which a suitable tolerance system must be worked out.

Compliance. In order to position components precisely, the structure of the system must be made and assembled with the necessary tolerance. Robots of advanced generations have a technology which is able to handle unstructured and undefined conditions. However, this increases the price of the robot and impairs its operating speed (see chapter 6). The statistic average of accuracy normally used in construction cannot be applied for construction with robots, as it does not take into account all cases of minimum and maximum accuracy [12], [17], [18].

Prefabrication. In order to transfer a major part of the production from the construction site to prefabrication and thus substitute industrial for manual fabrication, assembly elements should be of high quality and highly intergrated. In the automized construction process with freely-programmable handling systems, the construction site is only the final production stage of buildings. Prefabricated, high-quality elements are sent to the construction site and installed there. In that case, the advantages of industrial production in a controlled environment of factories can be used in such a way for the *flexible* production of high-quality elements that the building time on the site can be reduced.

Standardization. In order to get exactly defined building systems, building parts must be standardized. The joints in particular must be quasi-identical, in order to make assembly possible in the first place. This means, they must be geometrically identical and physically similar. What is an advantage for automation is the fact that different elements from different manufacturers can be grabbed and assembled in the same way (see chapt. 4.4).

Part family formation. Group technology creates groups of products which can be handled and assembled by a similar equipment and in a similar way. The result is a higher degree of rationalization because fewer tools and auxiliary constructions are needed (see chapter 4.4). A lintel, for example, can consist of several normal blocks (see chapt. 4.4).

Efficiency. Large elements have the advantage of reducing the necessary number of assembly operations. Furthermore, installations can then be integrated into prefabrication more easily.

Here, a conflict of priority becomes apparent concerning the required flexibility in design and a resulting problem of optimation. The assembly elements should be chosen as large as possible, in order to minimize the number of assembly cycles necessary, but still fulfil the required flexibility in design of a building part!

Large elements reduce the overall error, because first, fewer elements are needed and second, fewer interfaces (geometric, electric, sanitary, etc.) result, which get dirty rapidly on the construction site. However, they have the disadvantage of being heavier and more difficult to handle [13], [14], [15].

Flexibility. A greater flexibility in design can be achieved with the automatic assembly of sufficiently small, standardized, functional and essential assembly elements. Thus, flexible automation with robots favors a more individual design of building objects economically!

Auxiliary constructions. They should not be necessary !

Handling. In order to be transported without difficulties, parts should be designed in such a way that their center of gravity coincides with the gripper axle.

4.3 Philosophy in the automation of building assembly systems

Numerous similar, complementing, but also contrary suggestions to the automation of overground working assembly are widely known (see [6], [7], [8], [9], [10], [11], etc.). They aim at solving different partial aspects of complex tasks. As a result, seemingly contrary approaches may complement one another and have their justification at the same time. Therefore, different philosophies are mentioned here and some of them explained more in detail.

4.3.1 Use of common assembly elements

As to their weight and dimension, commercial bricks are adjusted to the ergonomics of the mason. Consequently, it can hardly make sense to draft an automatic assembly system, which assembles large, vertical and even building walls with these small bricks without considering the entirely different ergonomics of the robot. If, however, no larger assembly elements are available at a favourable price, only such a system may possibly lead to a competitive solution [7], [9].

4.3.2 Use of mortar

Mortar is used to connect blocks and so to offset measuring differences of the blocks and unevenness of the block layers and thus make a smooth transfer of pressure possible [10]. There are two reasonable possibilities:

1. level dimensionally inaccurate bricks in an underbed

   or

2. bond or drily/butt join dimensionally accurate bricks.

From the first to the second possibility, high-quality assembly elements save adjustment work and, as intended, transfer part of the production into industrial prefabrication (see chapt. 4.2). For the application of a bonding agent as well as for the spreading of mortar, standard solutions are available on the market, which can easily be entered into the automized assembly process, e.g. [19]. What is important is the question if dimensionally accurate bricks are assembled 'dry' or dimensionally inaccurate bricks assembled 'wet' (see chapt. 4 in Robotic Building block assembly system).

Broad underbed. In traditional building assembly dimensionally inaccurate bricks are placed in an underbed. The mortar does not so much serve as a binding material, because the strength of the resulting joint usually falls behind the strength of the assembly elements used. The major function of the broad layer of mortar is the tolerance adjustment of dimensionally inaccurate assembly elements. Furthermore, it offsets inaccuracies of positioning which result from the dirty block joint surfaces. In the manual building assembly, the bricks must be adjusted, i.e. levelled, by water balance and guidance. Dimensionally inaccurate bricks would otherwise lead to joints with an undefined geometric position. [10], [20], [21].

Thin underbed. A thin layer of mortar is used for the walling up of special blocks which are particularly true to size [10]. The use of the thin mortar or bonding agent requires dimensionally accurate assembly elements. In this case, only an exact measuring of the first layer is necessary. The overall error of the subsequent block layers is then determined by the measuring tolerance of the blocks (see chapt. 8). For subsequent layers, the time-consuming levelling by means of mortar is no longer necessary [1].

Dry blockwork. The term 'dry blockwork' usually refers to a blockwork of rubble stones which are joined without mortar and with little treatment as succinct as possible, i.e. without joints and gaps. But it is also used for accurate blocks, which are bricked without later composite action [20], [21]. The statement:

"Dry blockwork is unsuitable for automation due to lacking offsetting possibilities and the higher demands on manufacturing accuracy. Furthermore,.blockwork with later composite action is unfit for automation because of the additional working processes." [10]

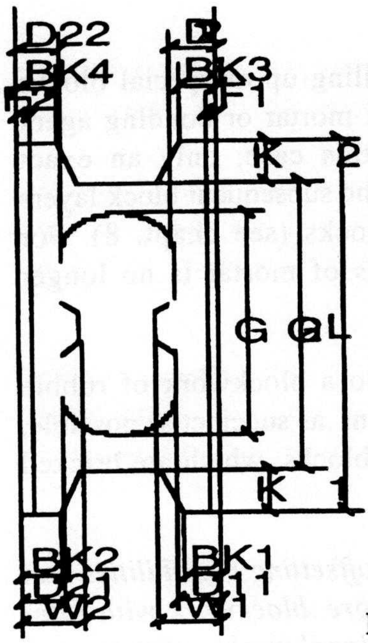
must be clearly contradicted. Completely opposite to the quoted opinion this type of assembly is a major simplification compared to the construction with mortar. With such a wall, only the first layer must be adjusted since the wall elements have minor measuring tolerances. A slight impairment may occur due to traces of dirt on the surfaces, however, prior to each jointing process, those can be cleaned preventively with little expenditure (e.g. by compressed air). Similar conditions can be found with cavity blocks, which are jointed at first without connecting material and afterwards filled with concrete [3], [20], [21].

In this assembly method the concrete filling can be done after a wall has been built. The permanent use of mortar necessary in conventional blockwork on every single block or at best on every layer of blocks can be avoided.

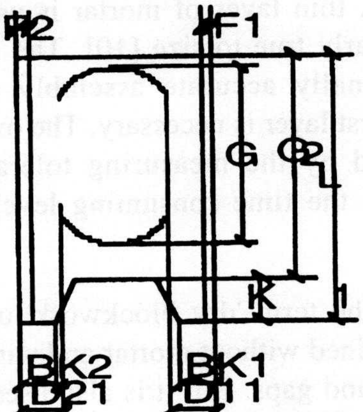
4.4 The wall elements used

4.4.1 Description of the blocks

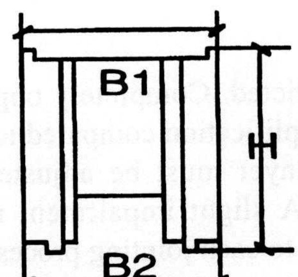
The experimental plant of gantry robots used cavity blocks as wall elements which were made by various cavity block producers (fig.8).



Normal block



Special block



B Block width

BK Cone width

D Wall thickness

F Feather width

G Gripping width

H Block height

K Cone depth

L Block length

W Bulb thickness

B1	B2	BK 1	BK 2	BK 3	BK 4	D1 1	D1 2	D2 1	D2 2	F1	F2	G1 1/1	G2 1/1
175	175	35	35	35	35	35	35	35	35	20	20	375	295
175,4	175,3	36,2	36,04	35,45	36,22	33,38	32,5	33,5	34,25	20	20,06	375,1	288,4

G1 1/2	G2 1/2	G1 2/3	G2 2/3	G1 3/4	G2 3/4	H	K1	K2	L 1/1	L 1/2	L 2/3	L 3/4	W1	W2
187	-	261	-	311	-	252	61	61	497	248	322	372	-	-
186,6	134,2	260,2	207,2	309,2	255,6	249,9	6092	61,1	496,0	249,0	324,4	373,2	58,6	59,7

Fig.8. Block measurements: Comparison of producer indications (top row) with measured averages (bottom row) in [mm].

Block types. Available are 3 different block widths (17.5 [cm], 20 [cm], 24 [cm]) and 5 different block variations each. Those are normal blocks, 3 different special blocks as partition blocks (1/2 blocks, 2/3 blocks, 3/4 blocks), corner blocks or wall finishing blocks (3/4 blocks) and miter elements (see fig 8).

The block system of 20 [cm] wide blocks differs mostly in width from those of 17.5 [cm] width and in so far as all partition blocks can at the same time be used as corner or finishing blocks.

The block system of 24 [cm] wide blocks, however, differs also because it has conic gripping surfaces inside!

The block systems are described in fig. 9 regarding their geometric measures (length, height, width), type, position and number of possible gripping areas and their suitability for wall finishing [3].

The lintels. To this block system provisional lintels were built which correspond in their measurements and connection type (slot/feather) to blocks. They are 1497 [mm] long and their weight is about the same as that of a normal block. They are constructed in such a way that they can be grabbed just like normal blocks.

Usage. Those blocks are used in housing construction for partition walls as a two-leaf blockwork (2* 17,5 [cm]) and for supporting interior walls. They are bricked as dry blockwork and afterwards filled with concrete B 15 to the height of a storey [3].

Characteristics. The filled blockwork reaches a compression stength of 20 [N/mm2]. According to producer indications, the measuring tolerances of the blocks are theoretically minor (+/-0.5 [mm]). The measuring tolerances stated are adhered to in those places relevant for mechanical construction (length, height, width, etc.). For automized building assembly, however, even minor tolerances in entirely different places of the blocks (cone, cylindrical gripping surfaces inside, etc.) are important. In these places measuring tolerances are obviously not adhered to (fig. 8). The blocks have a slot and feather system, which is supposed to facilitate assembly. The material of the blocks is bloating clay. The density of the material is 0.9 or 1.4 [kp/dm3]. The resulting weight of normal blocks ranges from 14 to 15 kg (see [3]). The blocks can be grabbed as described in chapter 6. As a rule, all undivided partition blocks can be bricked instead of normal blocks. Different grabbing possibilities may then be advantageous.

4.4.2 Discussion of the cavity block system regarding its suitability for automized assembly

Slot and feather system. Cavity blocks show a horizontal slot and feather system alongside the blocks, which is supposed to facilitate assembly. This means that theoretically those blocks should be locked in the cross direction by means of the slot and feather system. This slot and feather system is not compliant, however, due to the missing cone and is furthermore formed so insufficiently on one side due to the manufacturing method that it is often no longer visible. In addition, it must be considered that unfortunately, the feather of the 17.5-corner blocks is not interrupted, which leads to vertical errors in position especially in corners. These errors add up, unless the feather is later removed at these places manually. The producers' explanation is that normally those blocks are only used for straight interior walls without corners. All this leads to the slot and feather system effecting a higher positional insecurity rather than assisting assembly. This statement holds true for manual as well as automized bricking. A similar system (e.g. conic side areas), which could offset the positional errors from one block to the other and thus the gap widths endwise is not intended.

Gripping areas. Normal bricks have a conus form on all possible outside gripping areas which fosters the compliance cross-block in connection with a corresponding gripper. On the insides of all blocks, there are cylindrical recesses, which also support the compliant gripping cross-block. Likewise, in the middle of the normal blocks, there are two conically-formed bulbs to the same effect. There are no special mechanisms which support the compliance lenghtwise. But the positional tolerances of the gripping areas are minor, see chapter 4, so that a compliant gripper in the longitudinal direction of the block is perfectly sufficient.

- The blocks can be grabbed better when placed upside down. The gripper jaws (fig.16) have a longer working surface, as the recesses of the blocks are now at the bottom, where the gripper does not catch anyway [1], [17].
- As gripping areas which are far apart effect a higher compliance than those close together, positional errors can be offset better with larger blocks [1], [17].
- *The cone form shows a higher compliance than the cylinder form,* because with the latter, the gripping area is continually steeper to the gripping direction; with which the sliding friction of the gripper jaw on the gripping area rises constantly until its final fitting point has been reached so that often during the grabbing process the required final position of the gripper in the block is not reached. If the griping area has the cone form, however, there is a steady sliding friction during the grabbing process [1], [17].
- As a rule, gripping from the inside is more reasonable than gripping from the outside, because the gripper jaws close when they let go off the block and there is no danger of collision with other building elements around that block. *Therefore the blocks would be designed more suitable for automation, if their conic gripping areas were as far towards the outside as possible and could be grabbed from the inside [1],[17]!*

Measuring tolerances. Measuring tolerances are minor compared to other commercial blocks. According to producer indications, they amount to +/-0.5 [mm] (see fig. 8 and 9). Therefore, resulting assembly errors are relatively small [17] and the tolerances of the erected walls no larger than with walls where the blocks were levelled out in a mortar underbed.

Symmetry. It makes sense that the normal blocks can be grabbed symmetrically and thus the point of gravity lies on the crossing of gripping axis and Z-axis. This minimizes the moments of inertia of the block - following the law by Steiner (see chapt. 4.2) - and the moments resulting from gravity around the TCP (Tool Center Point) and makes the handling of the blocks easier. Unfortunately only the normal blocks of this block system can be grabbed symmetrically.

Dimension. The blocks are comparatively large. Consequently, the number of assembly operations necessary for the construction of a wall is small and the whole assembly process is shortened. Few elements with minor measuring tolerances reduce the overall error. An additional effect is that the number of block-joints is small. Traces of dirt (e.g. small pieces from porous blocks) deposited on the joining areas have therefore got a minor influence in the measuring tolerances of the walls [17]. The dimension of these blocks and their weight, of course, have a significant influence on their handling (see chapt. 4.2). Since cavity blocks have a hollow space, two blocks can easily be grabbed from the inside at the same time, which increases the efficiency of the automized building assembly considerably.

Element structure and element variations. The blocks have a clear and simple form. There are only 5 different assembly elements (see above). Special blocks and normal blocks are very similar. They follow the basic rule of group technology (see chapter 4.2). The result is that the blocks can all be grabbed by the same gripper, and assembly operations are similar. Consequently, only few different assembly operations need to be used [17]. The simplicity of the structure facilitates the production of elements as well as automation of assembly.

Assembly. The blocks are cavity blocks with few measuring tolerances and can be assembled as dry blockwork. As concrete is filled in subsequently to the height of a storey and due to possible strengthening with armoring steel, the wall gets additional stability. As no mortar needs to be used between the blocks, and the blocks need not be adjusted explicitly [17], this method of bricking is the easiest and at the same time the fastest and thus also the most suitable for automation (see chapt. 4.3.2). In an automatic process, the filling of concrete block by block would probably be more adequate because an even filling can be secured more easily, auxiliary constructions are not necessary (see chapt. 4.2) and the danger of subsequent displacement is lower [1], [20], [21].

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