DRYWALL JOINT FINISHING: PRODUCTIVITY AND ERGONOMICS

By John G. Everett,[1] Member, ASCE, and Dennis L. Kelly,[2] Associate Member, ASCE

ABSTRACT: Gypsum drywall panels are used extensively for wall cladding and structural fireproofing. Most interior building walls are of sufficient length and width to require at least two panels of drywall for complete coverage. Generally speaking, in residential construction, boards are placed horizontally (perpendicular to studs), and in commercial construction, boards are placed vertically (parallel to studs). This paper analyzes the effect of drywall panel and joint orientation on joint finishing operations. Productivity comparisons are made by investigating the total quantity of joint produced, productivity rates for various types of horizontal and vertical joints, and total time required to finish the joints. For typical residential applications, horizontal joints require less time to finish. For many commercial applications, vertical joints require less time to finish. However, there are many exceptions. Contractors and designers can save time and money by selecting the proper orientation. The locations of the joints on the wall also affects the motions and positions the craft worker must endure to complete the work. Professional finishers prefer horizontal joints because they greatly reduce the ergonomic stresses associated with bending down and reaching overhead.

INTRODUCTION

Gypsum and Drywall

Mineral gypsum has long played an important role in the construction industry due to its bonding and fire retarding properties. One of the earliest recorded uses of gypsum is found in Egypt, where it was mixed with lime for use as mortar and plaster to bond and cover the large stones of the Pyramids. Early Roman records indicate an appreciation for the fire-retarding qualities of gypsum plaster (Erwin 1990).

Over the centuries, gypsum has grown in popularity as a construction material. In the late 1920s and early 1930s, narrow gypsum lath panels were introduced as a replacement for wood or metal lath for wall plaster. The late 1930s saw the development of wider gypsum panels with an integrated joint treatment system (*Gypsum* 1992). This simple, innovative system has virtually replaced earlier wood or metal lath and plaster systems.

Today, gypsum panels are used extensively for wall cladding and structural fireproofing. Also known as drywall, gypsum wall board, plaster board, or by the registered U.S. Gypsum brand name SHEETROCK, gypsum panels are common wall-cladding materials in both residential and commercial construction.

The early popularity of gypsum panels was largely due to its considerably lower job-site water requirement and its rapid finishing time compared with the wet plaster system. This allowed for more expeditious sequencing of subsequent construction activities and project completion. Today, the popularity of drywall is largely due to its low overall cost due to material inexpense and low labor demand. Speed of installation, flexibility, fire resistance, and high sound-attenuating qualities contribute to and assure the continued popularity of drywall.

Annual gypsum panel production in the United States since 1987 has been nearly 19 billion square feet of regular and Type X gypsum panels (*Construction* 1996). This is an area equivalent to the greater Detroit metropolitan area. If the annual production of 4 ft (1.22 m) wide panels were placed end to end, the ribbon would circle the earth 36 times. In construction dollars, drywall material and installation accounts for about \$8.7 billion of construction annually.

The principle ingredient of drywall is mineral gypsum. Gypsum is a commonly occurring sulfate mineral of composition $CaSO4 \cdot 2H2O$, of which 21% is water. It is found in sedimentary deposits formed as seawater evaporites or in association with limestones, shales, marbles, and clays (Hurlbut and Klein 1977). Drywall is manufactured through a process of heating mineral gypsum to drive off the combined water. The product of this process is called calcined gypsum [calcium sulfate hemihydrate ("Standard" 1991)], and it is mixed with starch, water, pregenerated foam (for density reduction), and other additives to form a thick paste. This mix is sandwiched between a heavy finish paper and backing paper and passed through rollers to form the desired shape and thickness. The slurry of gypsum and additives bonds to the paper and sets in 3–4 minutes. It is then cut to length and heated to drive off residual water (Allen 1990). The finished product has a smooth finished surface, paper-wrapped beveled side edges, and cut unfinished ends. Type X, a special fire-resistant drywall, differs from other drywall in that it contains fiberglass or other reinforcement to provide support for the gypsum when exposed to the calcining effects of fire. Type X rated drywall 1/2 in. (13 mm) and 5/8 in. (16 mm) thick provide 3/4 and 1 hr fire resistance, respectively ("Standard" 1991).

The typical drywall system consists of 1/2 or 5/8 in. (13 or 16 mm) thick, 4 ft (1.22 m) wide × 8, 9, 10, 12, 14, or 16 ft (2.44, 2.74, 3.05, 3.66, 4.27, or 4.88 m) long gypsum panels cut to length and nailed, screwed, and/or glued to wood or metal studs or firring. The panels can be oriented either parallel or perpendicular to the studs. Orientation of the panels will be discussed in detail below. The panels are cut using a knife to score the face paper, then bent to break the board along the cut. The backing paper on the reverse side is then cut, and rough edges of the broken gypsum surface are trimmed. Panels may also be cut using a variety of saws. Most boards are hung with the beveled edges abutting the beveled edges of the adjacent board. In some cases, butt joints are required when the wall length or height exceeds the length of the longest panel available. Hanging drywall constitutes roughly 50% of the total labor cost involved in the system (*Building* 1997).

Joints

After the drywall is hung, the joints between panels must be treated for concealment and fire protection. The treatment typically consists of a three-coat application of a specially formulated joint compound. The first or base coat consists of a

[1]Asst. Prof. of Civ. and Envir. Engrg., Univ. of Michigan, 2352 G. G. Brown, Ann Arbor, MI 48109-2125.

[2]Proj. Mgr., Turner Constr. Co., 277 Gratiot Ave., Ste. 300, Detroit, MI 48266.

Note. Discussion open until March 1, 1999. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 5, 1997. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 124, No. 5, September/October, 1998. ©ASCE, ISSN 0733-9634/98/0005-0347–0353/ \$8.00 + \$.50 per page. Paper No. 15699.

J. Constr. Eng. Manage., 1998, 124(5): 347-353

paper or fiberglass reinforcing tape embedded in joint compound and centered over the seam. This is applied by hand using a drywall knife or through the use of dispensing tools known as the "banjo" and the "bazooka." A second coat fills the remainder of the beveled depression between panels. The third or finish coat is applied and trowel finished to give the wall a smooth, finished surface. The second and final coats are applied after sufficient time is allowed for the drying and light sanding of previous coats to assure a surface free of defects.

A midwall joint can be either a beveled edge joint or an end-of-panel (or cut edge) butt joint. A beveled edge joint results when the beveled edges of vertically or horizontally oriented panels are placed side by side. A butt joint results from the abutment of the unfinished panel ends when panels are placed end to end. Butt joints require additional finishing time, because the reinforcing tape and joint compound sit on the surface of the panel rather than in the depression formed by the adjacent preformed beveled edges. Butt joints must be made approximately twice as wide as beveled edge joints so that the joint compound can be feathered out over the surface of the panel to conceal the joint.

The process of filling and sanding drywall joints requires a minimum of six separate occasions for the craft worker to physically work or pass along the length of the joint. Each occasion can involve 1–4 passes of a hand-held tool over the joint. This can result in a total of 8–14 passes of the hand over the total length of the joints. Joint orientation and quantity, therefore, have a significant impact on the time required to finish a drywall-clad wall. The finishing process constitutes the remaining 50% of the labor costs involved in installing drywall (*Building* 1997).

Objective

The objective of this paper is to analyze the effect of drywall panel and joint orientation on joint finishing operations. Productivity comparisons will be made by investigating the total quantity of joint produced, the productivity rates for various types of horizontal and vertical joints, and the total time required to finish the joints. The locations of the joints on the wall also affect the motions and positions the craft worker must endure to complete the work. Ergonomic comparisons of horizontal and vertical joints will be made by evaluating the number of times the finisher must bend down and reach overhead.

PANEL ORIENTATION

Most walls are of sufficient length and width to require at least two panels of drywall for complete coverage. Drywall panels may be placed either parallel or perpendicular to wall studs spaced 24 in. (0.61 m) or less on center. A decision is made at the time material is ordered regarding the orientation of the board with respect to the studs. Factors that influence this decision are the designed fire rating requirements of a wall, ease of application, material waste, wall stiffness, ease of the subsequent joint treatment, and appearance of the finished surface.

Considerable difference in opinion and practice exist between workers and management in commercial and residential construction as to which board orientation is better. Generally speaking, in residential construction, boards are placed horizontally (perpendicular to studs), and in commercial construction, boards are placed vertically (parallel to studs).

Some of the reasoning offered by several drywall contractors for these practices is given below. Not all of this reasoning is entirely sound and some is contradictory. Residential contractors and finishers generally prefer horizontal orientation (perpendicular to studs) for the following reasons: less joint to finish, lower finish cost, the majority of midwall joints are accessible from a standing position, reduces bending and reaching overhead, produces a better finish by concealing waves due to warping and irregularities in wood studs, less control over stud locations [not always 4 ft (1.22 m) on center], and less waste.

Some commercial contractors and finishers prefer horizontal orientation (perpendicular to studs) because this produces a stiffer wall, it minimizes the length of joint needing treatment, it yields a better looking wall, and it reduces bending and reaching overhead. Other commercial contractors and finishers prefer vertical orientation (parallel to studs) for the following reasons: continuous edge support from studs, required for fire rating, reduces quantity of undesirable butt joints, less waste on large jobs (board may be ordered from factory to exact length needed), required by some architects for better wall finish, and panels do not have to be lifted to the top of the wall, because they are supported by the floor.

From the manufacturers' perspective, the U.S. Gypsum *Construction handbook* states that perpendicular (horizontal) placement of panels relative to studs places the strong direction of drywall perpendicular to studs and therefore produces a stiffer wall (*Gypsum* 1992). Either orientation is acceptable as long as there is proper backing, allowing for proper fastener and support spacing. Care should be taken to avoid placing wrapped (beveled) edges against unwrapped edges. This may lead to differential expansion and eventual cracking.

Numerous fire resistant wall designs are presented in the Gypsum Association publication *Fire resistance design manual* (1994). For example, 32 metal and wood stud wall designs for drywall placed parallel to studs and 12 metal and wood stud wall designs with drywall placed perpendicular to studs have 1 hr fire ratings. Eight of these designs are proprietary to specific drywall manufacturers (*Fire* 1994). This indicates that, while fire ratings must be considered, they are not a critical factor in the decision.

Joint Orientation and Quantity

The orientation and location of the drywall panels dictates the orientation and location of the joints to be finished. Vertically hung drywall panels produce vertical joints that run from the floor to the top of the wall. The lateral position of vertical joints on the wall depends on the location of the drywall panels, but the vertical joints will be spaced 4 ft (1.22 m) on center due to the 4 ft (1.22 m) width of the panels. The joints may be positioned to fall over any stud, but will always extend from the floor to the top of the wall. To finish the joint, the craft worker is required to bend over to the floor and to work from stilts or a bench to reach the joint at the top of the wall.

Horizontal joints run from corner to corner. Adjustment to the height of the joint from the floor can be made by varying the height (panel width) of the panel nearest the floor. Most horizontal joints can be installed at a height within the reach of most craft workers, resulting in less bending and stepping up on stilts or a bench compared with vertical joints.

The quantity of joint for a given wall varies depending on the orientation of the drywall and the dimensions of the wall. Fig. 1(a) shows a wall 8 ft high × 12 ft long (2.44 m × 3.66 m). If the panels are hung horizontally, there will be 12 linear ft (3.66 m) of joint to finish, indicated by the heavy line. Fig. 1(b) shows the same 8 ft high × 12 ft long (2.44 m by 3.66 m) wall with the panels hung vertically. In this case, there will be two vertical joints, each 8 ft (2.44 m) in length, for a total of 16 linear ft (4.88) of joint, as shown by the two heavy lines. For this size wall, horizontal panels require substantially less joint finishing than vertical panels.

For other wall dimensions, vertically hung panels produce

J. Constr. Eng. Manage., 1998, 124(5): 347-353

less joint. Fig. 1(c) shows a 9 × 12 ft (2.74 × 3.66 m) wall with horizontal panels. Here there are two joints, each 12 ft (3.66 m) in length, or 24 linear ft (7.32 m) of joint to be finished. The incremental 1 ft (0.30 m) of height [compared to the 8 ft (2.44 m) wall] adds a second horizontal joint, the

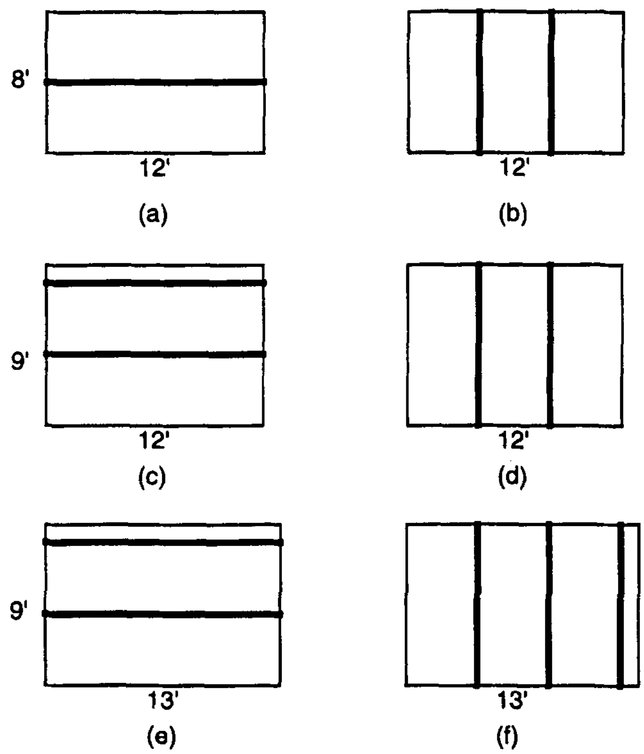

FIG. 1. Joint Length Varies with Different Wall Dimensions

full width of the wall. Fig. 1(c) shows the two horizontal joints at 4 ft (1.22 m) and 8 ft (2.44 m) from the floor, but this is not the only, nor even necessarily the most desirable, configuration. This issue will be discussed below.

If the panels are hung vertically, as shown in Fig. 1(d), there will be two joints, each 9 ft (2.74 m) in length, for a total of 18 linear ft (5.48 m) of joint. Clearly, in this case, vertical panels produce less joint to be finished.

If the 9 ft (2.74 m) wall is lengthened to 13 ft (3.96 m), the situation changes again. Fig. 1(e) shows that the wall has 26 linear ft (7.92 m) [two joints, each 13 ft (3.96 m)] of joint with horizontal panels. Fig. 1(f) shows that vertical panels produce 27 linear ft (8.23 m) [three joints, each 9 ft (2.74 m)] with vertical panels. Here, the horizontal orientation produces slightly less joint.

From Figs. 1(c and f), it can be seen that an increase in wall dimension perpendicular to the joint orientation produces a whole new joint at each 4 ft (1.22 m) increment. Additional increases in this dimension do not change the quantity of joint until the next 4 ft (1.22 m) module is reached. For increases in wall dimension parallel to the joint orientation, the total joint length increases but remains proportional to the wall dimension.

This type of analysis can be performed for any size wall to determine quantities of midwall joints to be finished. To facilitate comparison of different size walls to each other, the term "joint ratio" is introduced. Joint ratio is defined as the quantity of joint (linear ft) divided by the area of the wall (square ft). Fig. 2 shows a plot of joint ratio (lf joint/sf wall) versus wall length for four different wall configurations.

The lowest curve (squares) shows the joint ratio for an 8 ft (2.44 m) high wall with a horizontal joint. The joint ratio is constant at 0.125 lf joint/sf (4.68 cm/m^2) wall until the wall reaches 16 ft (4.88 m) in length. Here it is assumed that 16 ft

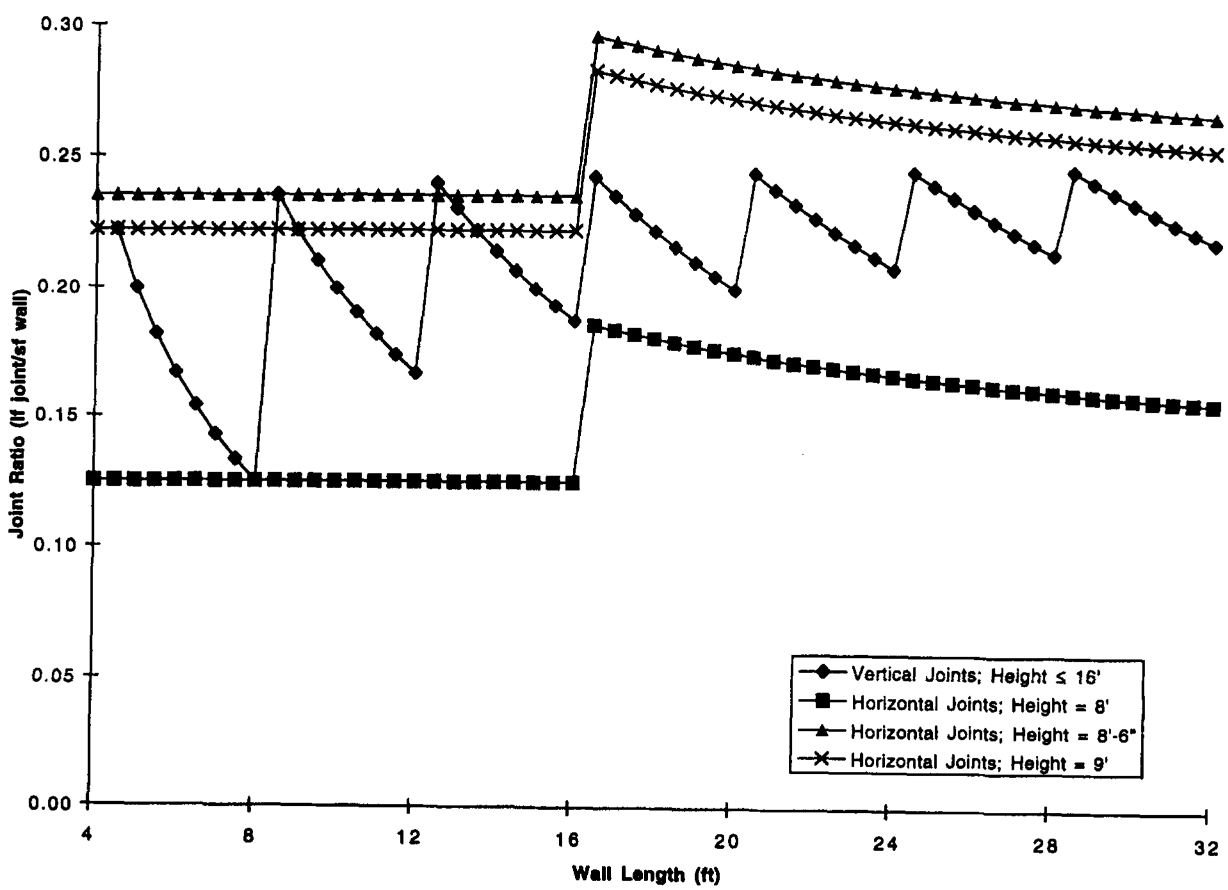

FIG. 2. Joint Ratio (lf joint/sf wall area) versus Wall Length for Various Wall Configurations

J. Constr. Eng. Manage., 1998, 124(5): 347-353

(4.88 m) panels are used. A slight increase in wall length, e.g., to 16 ft 6 in. (5.03 m), requires a full wall height vertical butt joint, so there is a quantum jump in joint ratio just above 16 ft (4.88 m) in wall length. With increasing wall length beyond 16 ft (4.88 m), the joint ratio decreases as the additional joint length gets divided over a larger wall area. Another jump occurs at 32 ft (9.75 m).

The top curve (triangles) shows a similar plot for an 8 ft 6 in. (2.59 m) wall with horizontal joints. In this case there would be a second horizontal joint [as in Fig. 1(c)], and the joint ratio would be nearly twice as large as for an 8 ft (2.44 m) wall. As for the 8 ft (2.44 m) wall, an increase in joint ratio occurs each time the wall length exceeds a multiple of 16 ft (4.88 m). A 9 ft (2.74 m) wall with horizontal joints (Xs) is similar to an 8 ft 6 in. (2.59 m) wall, but the joint ratio is slightly lower because the total joint length is the same while the wall area is larger.

The curve representing vertical joints (diamonds) applies to any wall height below 16 ft (4.88 m) (beyond this, a horizontal butt joint would be required). In this curve, the jumps in joint ratio occur at each 4 ft (1.22 m) increment, corresponding to the addition of a full height vertical joint.

Similar plots can be developed for any height and length wall, or for different length drywall panels, but the basic pattern remains as shown. From this chart it can easily be seen that for certain sized walls, one joint orientation clearly produces a lower joint ratio (and lower total joint) than the other joint orientation. To return to the examples in Fig. 1, for an 8 × 12 ft (2.44 × 3.66 m) wall, horizontal orientation has a lower joint ratio. For a 9 × 12 ft (2.74 × 3.66 m) wall, vertical orientation has a lower joint ratio. For a 9 × 13 ft (2.74 × 3.96 m) wall, the joint ratios are quite close for the two orientations.

It should be noted that the wall dimensions used throughout this paper are approximate. Normal drywall panels are exactly 4 ft (1.22 m) wide, but they are usually installed slightly raised off the floor, so a horizontal joint is more likely to be found at 4 ft 1/2 in. (1.23 m) rather than exactly 4 ft (1.22 m) off the floor. This may not appear to make much of a difference, but the next joint up would then be at 8 ft 1/2 in. (2.45 m), allowing a finished suspended ceiling to be installed at 8 ft (2.44 m).

Contractors can fudge an inch or two in wall width if necessary. For example, if a wall were 12 ft 1 in. (3.68 m) wide, it might appear necessary to install three full vertical sheets plus a one inch strip. This would be labor intensive and impractical because the thin strip would break during cutting, installation, or fastening. In practice, the installer would probably leave a one-half inch (13 mm) gap on either end, which would be filled in by the finisher. The installer could also install the adjacent, perpendicular wall panels first, thereby reducing the width of the wall by an inch or so, depending on the panel thickness.

The dimensions are also somewhat ambiguous, because it may not be clear whether the dimensions refer to the size of the wall before the drywall is installed or after. The room will shrink by an inch or so in both directions in plan after all the drywall is installed. These differences only shift the plots in Fig. 2 to the left or right slightly, but at some point as the wall dimension increases, there will be a quantum jump in the joint ratio as a whole additional joint is added.

PRODUCTIVITY MEASUREMENT

Total joint length and joint ratio are measures of the quantity of joint to be finished. Probably of more interest to most construction engineers and managers is the time or cost to finish the joints. This requires that productivity rates be known for different joint orientations and locations. The time required to finish a vertical joint and a horizontal joint of the same length are not necessarily equal, and the location of the joint [i.e., near the floor, 4 ft (1.22 m) off the floor, at full reach, beyond full reach] must be considered.

This paper analyzes only midwall joints. The finisher must also work the inside and/or outside corner joints around the perimeter of the wall, but these are constant for a given wall regardless of drywall orientation and are therefore not included in calculations here. Similarly, the finishing of nail or screw heads is assumed to be equal for both orientations, and is not included in this analysis.

Vertical and horizontal beveled joint finish rates for the first (base), second (fill), and third (finish) coats were measured for three professional finishers. Finishing productivity rates, measured as minutes per linear foot of joint (min/ft), were determined from field observations of drywall finishers on jobs with joints in both orientations.

This is easier said than done. It is easy enough to find residential contractors finishing horizontal joints and commercial contractors finishing vertical joints, but it is difficult to find situations where the same finishers could be observed finishing both horizontal and vertical joints. The goal was to compare finishing rates for different joints without having to account for differences among craft workers.

Most of the data was collected at the School of Social Work building project on the University of Michigan campus. This project was typical of many office buildings with many small offices around the perimeter of each floor. Many of the offices were configured such that the owner and drywall subcontractor were willing to install the drywall panels horizontally. Normally the entire building would have had the panels hung vertically.

Field measured productivity rates are shown in Table 1. For each finisher, data were collected for the first, second, and third coats for low horizontal beveled joints, high horizontal beveled joints, and vertical beveled joints. The values shown are the average for three finishers for several of each type of joint. The finishers were amazingly consistent for each type of joint; after all, they have been performing this work day in and day out for many years. However, there were differences among the finishers. It should come as no surprise that some workers are faster than others. The values reported in Table 1 are valid for the finishers observed, but the results may vary for other finishers on other projects.

An average worker (50th percentile male) with a drywall knife in his hand can reach to 6 ft 10 in. (2.08 m) from a standing position (Differient et al. 1981). Therefore, a distinction is made between work performed standing on the floor and work performed standing on stilts, a bench, or an inverted joint compound bucket. For horizontal joints, low typically means the joint was about 4 ft (1.22 m) above the floor, and high means the joint was about 8 ft (2.44 m) above the floor.

For vertical joints, the finisher can work the joint from the floor to about 6 ft 10 in. (2.08 m) above the floor. This range was originally considered the low vertical range. The portion of the vertical joint above this height requires standing on one of the aforementioned devices. This was originally considered the high vertical range. However, great differences in work

TABLE 1. Field Measured Productivity Rates for Finishing Drywall Joints (min/ft)

Coat (1)	Low horizontal bevel joint (2)	High horizontal bevel joint (3)	Vertical bevel joint (4)	Vertical butt joint (5)
First (base)	0.13	0.16	0.15	0.30
Second (fill)	0.11	0.19	0.11	0.22
Third (finish)	0.11	0.17	0.11	0.22

J. Constr. Eng. Manage., 1998, 124(5): 347-353

"style" occur among workers. Some work the entire height of the joint continuously, stepping up and down from a bucket as they work. Others work the low portions of several vertical joints at one time, and come back later to complete all the high portions. Some prefer stilts; others prefer a bucket, a bench, or whatever is handy. Because of all these differences, especially the inability to separate the high and low portions for some workers, all the high and low values for vertical joints were combined into a single value for each coat for each finisher.

Limited data was collected for butt joints; however, drywall installers avoid these joints whenever possible and therefore they make up only a small fraction of the total joints. Butt joints take roughly twice as much time to finish compared with an equal length beveled joint (as shown in column 5 of Table 1), but more importantly, they are nearly impossible to hide, because there is always a ridge in the finished wall. For long walls with horizontal panels and joints, butt joints (which will be vertical) are inevitable. In this case, the contractor may elect to install the panels vertically and avoid the problem. In residential construction, where the panels are almost always installed horizontally, the walls sizes are usually short enough that few butt joints are required.

In commercial construction, where the walls are more likely (compared to residential construction) to be longer than the drywall panels and the ceilings are more likely to exceed 8 ft (2.44 m) (requiring a second horizontal joint), the panels are almost always installed vertically. In this case, butt joints only occur at heights greater than the length of the panel. Few ceilings are high enough that this is a problem. Most of the butt joints that do occur are above the height of the finished (suspended) ceiling. Some of these joints may need a base coat for fire resistance (sometimes called "firetaping"), but the appearance is not critical, so they receive less careful craftsmanship than a joint that would show. Second and third coats are typically not required and not applied.

The total time required to finish the midwall joints on a given wall may be calculated by the following equation:

$$\text{Time} = \sum_{i=1}^{2} \sum_{j=1}^{3} \sum_{k=1}^{3} (A_i \times JR_i \times P_{ijk}) \tag{1}$$

where A_i = wall area; JR_i = joint ratio; P_{ijk} = productivity rate; i = 1 for wall area below 6 ft 10 in. (2.08 m) and 2 for wall area above 6 ft 10 in.; j = 1 for horizontally oriented beveled joints, 2 for vertically oriented joints, and 3 for vertically oriented butt joints; and k = 1 for the first (base) coat, 2 for the second (fill) coat, and 3 for the third (finish) coat.

Eq. (1) is simply the sum of the products of the total quantity of each type of joint multiplied by the appropriate productivity rate. Combining the wall areas and joint ratios from Fig. 2 and the productivity rates from Table 1 produces Fig. 3, which shows the total time (minutes per square foot of wall area) required to finish each type of wall. The general shape of the plots in Fig. 3 is similar to those in Fig. 2, but the differences in productivity rates have shifted the plots relative to each other.

From Fig. 3, it can be seen that for 8 ft (2.44 m) high walls up to 16 ft (4.88 m) in length, horizontal joints require less finishing time. Additional length beyond 16 ft (4.88 m) introduces the vertical butt joint and makes horizontal orientation less desirable relative to vertical. Using the joint ratios alone (Fig. 2), horizontal orientation is always preferred for 8 ft walls. From Fig. 3, for 8 ft 6 in. (2.59 m) and 9 ft (2.74 m) walls, vertical orientation is always preferred. Using joint ratios alone (Fig. 2), one might pick either orientation.

In residential construction, walls are typically 8 ft (2.44 m) high and less than 16 ft (4.88 m) long, so it is appropriate that

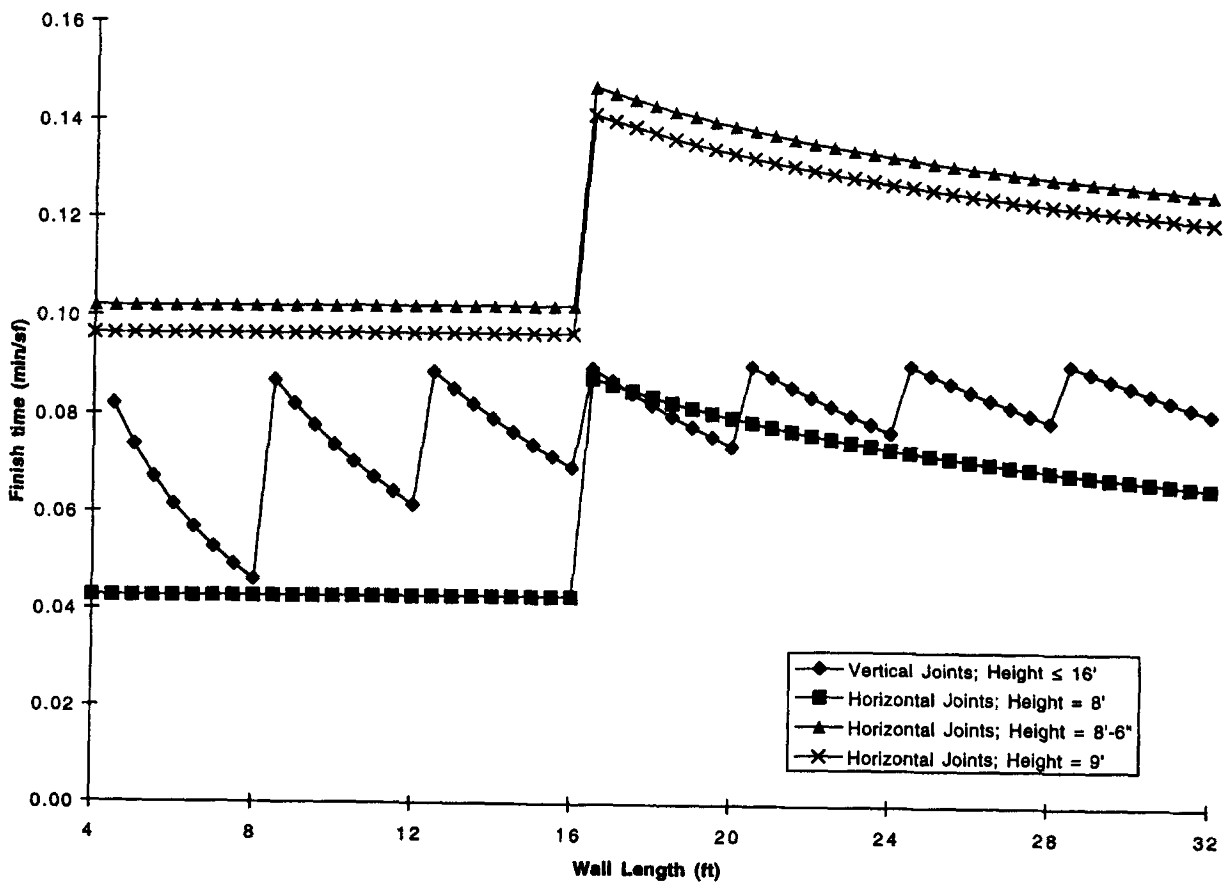

FIG. 3. Joint Finishing Times (min/sf wall area) for Various Wall Configurations

J. Constr. Eng. Manage., 1998, 124(5): 347-353

the drywall panels are installed horizontally. In commercial construction, walls are often more than 8 ft (2.44 m) high and often more than 16 ft (4.88 m) long. It is appropriate that they be installed vertically.

Despite the fact that no drywall contractor interviewed had ever considered the concepts presented in this paper, industry practices seem to have evolved to minimize finishing times in most cases. However, in most residential construction projects, there are some walls, such as those in living rooms with cathedral ceilings, that would have reduced finishing times if panels were placed vertically rather than horizontally. In commercial construction, many walls can be found that would be finished in less time with horizontal panels. Offices and small rooms often have 8 ft (2.44 m) ceiling heights and wall lengths less than 16 ft (4.88 m). Designers and contractors wishing to minimize costs and maximize speed of construction should evaluate each wall for the most efficient panel orientation, rather than simply installing all panels in the entire building the same way.

ERGONOMICS

The analysis above has focused strictly on productivity analysis and estimating finishing times. This is typically the primary concern of the contractor. However, interviews with the finishers reveal that they overwhelmingly prefer horizontal joints and are relatively unconcerned with productivity rates. The reason for this is that horizontal joints allow the finisher to work at a constant, relatively comfortable, height. Much of the time, they are standing on the floor working on a joint at about 4 ft (1.22 m) above the floor. For high horizontal joints, the finisher must strap on a pair of stilts or step up on a bucket, but once that is done, the finisher works at a constant height, which may be quite comfortable, especially with tall (but often illegal) stilts. (Many finishers are quite adept at "walking" a bucket around by shifting their weight and twisting their feet, and therefore they do not have to constantly step up and down from the bucket.) With vertical joints, there is constant bending down to the floor, reaching well overhead, and stepping up and down from a bucket.

It is difficult to quantify the ergonomic stresses in terms compatible with the productivity figures, but in the long run, worker fatigue and musculoskeletal injuries of the knees, low back, shoulder, and neck will have a serious negative impact on productivity, workers' compensation insurance premiums, and project costs.

Ergonomists recommend that standing work be performed between knuckle height [approximately 30 in. (0.76 m) above the floor] and shoulder height [approximately 64 in. (1.63 m) above the floor]. Work below this range requires bending of the back and/or legs. Work above this range requires excessive reaching upward (Rogers 1993; Waters et al. 1994). Using these guidelines, one can divide the typical 8 ft (2.44 m) wall into three roughly equal height ranges. The lowest third of the wall [floor to 32 in. (0.81 m)] requires continuous bending down, the middle third [32 to 64 in. (0.81 m to 1.62 m) above floor] is relatively comfortable, and the upper third [above 64 in. (1.62 m)] requires constant reaching upward. Two of these three ranges place the worker in a very uncomfortable position and at risk for developing overexertion injuries (Armstrong 1993). When finishing vertical joints, the worker will be in the uncomfortable ranges two thirds of the time. When finishing horizontal joints at 4 ft (1.22 m) above the floor, the worker stays in the middle of the comfortable range the entire time.

To estimate the actual number of times a finisher bends down and reaches up during a day of finishing vertical joints, videotapes of finishers were reviewed. Over the course of an 8 hour day, the typical finisher bent down 746 times and reached up 835 times. While standing on the floor, the finisher

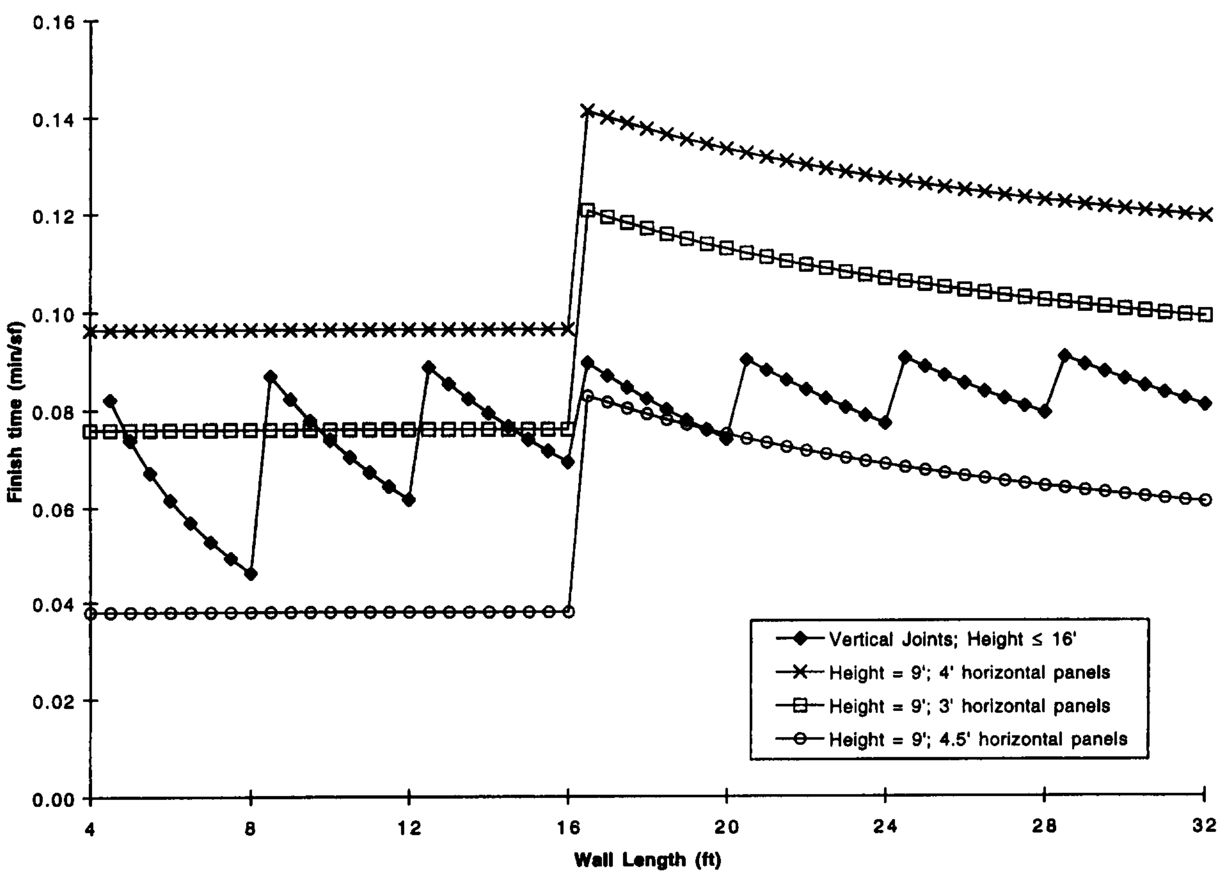

FIG. 4. Joint Finishing Times (min/sf wall area) for Hypothetical New Panel Sizes Compared with Conventional Panels

J. Constr. Eng. Manage., 1998, 124(5): 347-353

bends down relatively more often working the middle and low ranges; while working on stilts or a bench, the finisher reaches up more often, working primarily the upper range. This count agrees with a statement one of the finishers made, that in the course of a morning's work taping one hallway, he bent down three hundred fifty times. After that he stopped counting.

DRYWALL WIDTHS OTHER THAN 4 FEET

Standard drywall panels are 4 ft (1.22 m) wide and vary in length up to 16 ft (4.88 m). Recently, 54 in. (1.37 m) wide panels have become available in limited lengths (8, 10, and 12 ft) (2.44, 3.05, and 3.66 m) ("Gypsum" 1996). These panels offer the possibility of a single horizontal joint on walls up to 9 ft (2.74 m) in height; however, drywall installers who have used the 54 in. (1.37 m) wide panels emphasize that they are even heavier than normal 4 ft (1.22 m) panels and have not gained much popularity among craft workers.

It would be possible to manufacture drywall panels in smaller widths as well. For example, if panels were made 3 ft (0.91 m) wide, three panels could be installed horizontally for walls up to 9 ft (2.74 m) in height. There would still be two horizontal joints, so the joint ratio would be the same as for 4 ft (1.22 m) wide panels. However, the joints would be at 3 ft (0.91 m) and 6 ft (1.83 m) above the floor, both of which could be easily reached by a finisher standing on the floor.

Fig. 4 shows the projected finishing times for four configurations of 9 ft (2.74 m) high walls. The vertical joints (diamonds) and 4 ft (1.22 m) horizontal panels (Xs) are identical to the corresponding plots on Fig. 3. The open squares show the projected finishing times for the hypothetical 3 ft (0.91 m) wide panels, assuming all joints can be finished at the low horizontal beveled joint rate in Table 1. For walls from 8 to 16 ft (2.44 to 4.88 m) in length, 3 ft (0.91 m) panels would be about the same as 4 ft (1.22 m) panels from a productivity standpoint, but superior from an ergonomic standpoint.

The open circles show the 54 in. (1.37 m) panels, assuming they would be available in 16 ft (4.88 m) lengths. The finishing time would be much less than either of the current choices. These extra wide, extra long panels would be a bear to install, but with improved manipulators and handling devices, they may someday be competitive.

CONCLUSIONS

This paper has analyzed the effect of drywall panel and joint orientation on joint finishing operations. Productivity comparisons were made by investigating the total quantity of joint produced, productivity rates for various types of horizontal and vertical joints, and the total time required to finish the joints. It was shown that for 8 ft (2.44 m) high walls up to 16 ft (4.88 m) in length, horizontal joints require less finishing time than vertical joints. For most walls higher than 8 ft (2.44 m), vertical joints require less finishing time. This analysis confirms that the general use of horizontal panels among residential contractors and vertical panels among commercial contractors is appropriate. However, the paper also demonstrates that contractors and designers can save time and money by evaluating each wall for the most efficient panel orientation rather than simply installing all panels in the entire building the same way.

In addition to the productivity concerns, the paper has examined the joint orientation from an ergonomic standpoint. Horizontal joints are superior to vertical joints and are preferred by the craft workers. Horizontal joints greatly reduce bending down and reaching overhead as compared with vertical joints.

FUTURE RESEARCH

The effects of orientation on drywall hanging and the resulting quality of the finished surface have not been analyzed in this paper. Further research in this area may be desirable to determine the effect of joint orientation on overall drywall productivity. This paper has examined joint finishing performed by hand with a drywall knife. Other tools, including the bazooka, the banjo, and the box may speed up application of the joint compound and tape, but the joint compound must still be smoothed and wiped by hand. In this case, the productivity rates in Table 1 may need to be adjusted, but the joint ratios would remain valid. Local practice varies in the use of these tools. Some union collective bargaining agreements forbid the use of these tools.

ACKNOWLEDGMENT

This research was funded by Grant #5R03OH03154-02 from the National Institute for Occupational Safety and Health (NIOSH) whose support is gratefully acknowledged.

APPENDIX I. REFERENCES

Allen, E. (1990). *Fundamentals of building construction: materials and methods*. John Wiley & Sons, New York, N.Y.

Armstrong, T. A. (1993). *Analysis and design of jobs for control of upper limb musculoskeletal disorders*. University of Michigan, Ann Arbor, Mich.

Building construction cost data. (1997). 55th Ed., R. S. Means Company, Inc., Kingston, Mass.

Construction review. (1996). Vol. 42, U.S. Department of Commerce, Washington, D.C.

Diffrient, N., Tilley, A., and Harman, D. (1981). *Human scale manual 7/8/9*, MIT Press, Cambridge, Mass.

Erwin, A. E. (1990). "The evolution of space enclosure from mud and reeds to modern walls and ceilings." *ASTM Standardization News*, 18(12), 44–48.

Fire resistance design manual. (1994). 14th Ed., Gypsum Association, Washington, D.C.

Gypsum construction handbook. (1992). United States Gypsum Company, Chicago, Ill.

"Gypsum panel products types, uses, sizes, and standards." (1996). *GA-223-96*, Gypsum Association, Washington, D.C.

Hurlbut, C. S., and Klein, C. (1977). *Manual of mineralogy*, 19th Ed., John Wiley & Sons, New York, N.Y.

Rogers, S. H., ed. (1983). *Ergonomic design for people at work*. Van Nostrand Reinhold, New York, N.Y.

"Standard specification for gypsum wallboard." (1992). *ASTM C36-92*, ASTM, West Conshohocken, Pa.

"Standard terminology relating to gypsum and related building materials and systems." (1991). *ASTM C11-91*, ASTM, West Conshohocken, Pa.

Waters, T. R., Putz-Anderson, V., and Garg, A. (1994). *Applications manual for the revised NIOSH equation*. U.S. Dept. of Health and Human Services, Cincinnati, Ohio.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A_i = wall area;
i = variable depending on vertical location of wall area [above or below 6 ft 10 in. (2.08 m)];
JR_i = joint ratio;
j = variable depending on type of joint (horizontal, vertical, beveled, butt);
k = variable depending on joint compound coat (base, fill, or finish); and
P_{ijk} = productivity rate.

J. Constr. Eng. Manage., 1998, 124(5): 347-353