Unpredictable Nature and Cause of Cracks at Gypsum Panel Ceiling Joints Perpendicular to Framing

By Frank Woeste and Joe Loferski

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Introduction

In some arid parts of the Southwest, the occurrence and recurrence of cracks at taped gypsum panel (drywall) joints between panels in residential projects have been reported in trade magazines since the mid-1990s. In some homes of a project, one or two cracks or ridges appear at the finished drywall joint on the long side of panels which are typically installed perpendicular to a wood truss or solid-sawn-joist span. Cracks are more common than ridges, and we will refer to both collectively as "joint cracks."

Of course, homeowners are displeased when they see long and straight joint cracks forming in the center of their living room ceiling or other areas. Furthermore, even after they are repaired, many joint cracks recur on a seasonal basis. As will be discussed in depth, the factors that interact to produce joint cracks are the hygroscopic behavior of framing lumber and drywall that is driven by climate and occupants. The purpose of this article is to explain the unpredictable nature and cause of ceiling joint cracks (for example, see Figure 1) and the factors that interact to produce joint cracks in some homes while not in others.

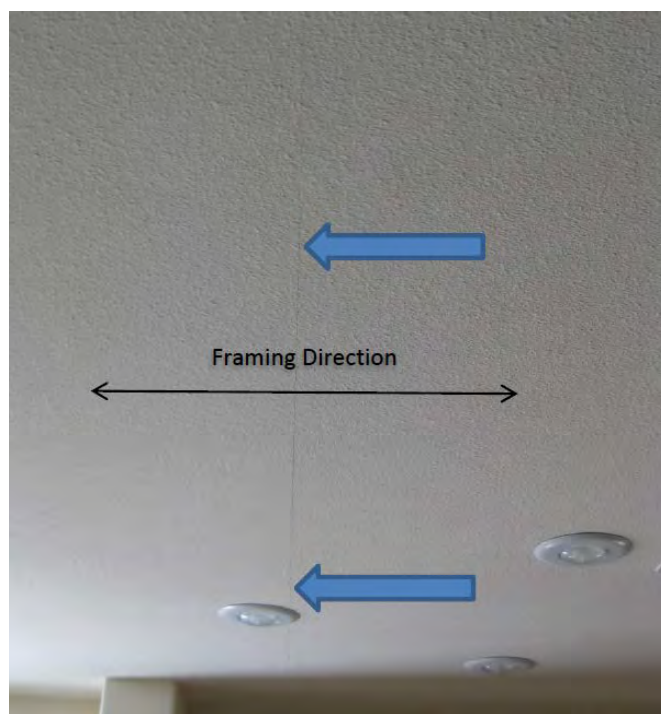

Figure 1. The trademark of the ceiling joint cracking problem is a straight line crack perpendicular to the framing direction.

Mechanism of Ceiling Drywall Cracks

Even when all *structural safety* aspects of the designed, fabricated, and constructed roof framing system are code-conforming and the ceiling drywall has been installed in accordance with applicable industry standards and building code requirements (as this article assumes), joint cracks can occur. To understand the mechanism of the ceiling drywall cracks, numerous physical facts, observations, and related research publications have been analyzed. The sections which follow summarize our discovery of information leading to the direct cause of ceiling drywall joint cracks.

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Hygroscopic Behavior of Lumber and Drywall

Both lumber and drywall panels are hygroscopic, meaning "water loving." Both products expand and contract based on the temperature (T) and relative humidity (RH) that surrounds the product. As an approximate rule-of-thumb for all species, lumber expands or contracts in the ratio of 1-25-50 corresponding to the longitudinal, radial, and tangential directions, respectively, of the log from which the piece of lumber is sawn.

Drywall has a "wood product" component – the paper adhered to both sides of the gypsum-based core. For the case of paper, the three directions of expansion or contraction are referred to as the "machine direction," "cross-machine direction," and the thickness direction. According to Caulfield[1], "The relative swelling in machine direction to cross-machine direction to thickness direction (x:y:z) is in the approximate ratio of 1:3:30."

Of course, the paper on both sides of the drywall panel is only one component of the panel and, as such, the interaction of the paper and gypsum-based core as affected by transient values of T and RH is very complicated. The fact that paper has a 1:3 linear expansion or contraction coefficient (in the x-y plane of the paper) suggested to us that drywall dimensional stability may also be affected by direction, that is, the panel long side direction may react to changes in RH differently that the 4-ft. panel direction. In a pilot study, we tested the dimensional stability of two types of drywall panels as affected by changes in RH. The results are presented later in this article.

Interaction of Paper, Edge Tape, Lumber, and Screws

The direct attachment of the drywall to the wood trusses or ceiling joists plays a critical role in producing ceiling drywall joint cracks. This section assumes that the drywall panels are directly attached to metal-plate-connected (MPC) wood trusses (2x4 bottom chord) with screws at 12-inches on-center (oc) and the truss clear span is 28'-8". To understand the physical interaction of drywall, edge tape, lumber, and screws, a hypothetical snapshot of residential construction in an arid region of the Southwest follows.

Thirty days after the roof truss installation, the truss lumber is approaching equilibrium moisture content (EMC) for a house that is framed (but without a ceiling) and subjected to typical climatic conditions for a specific month. EMC of a hygroscopic material refers to the moisture content of the material that will eventually be reached after being placed in a new and constant T and RH environment. In reality, hygroscopic building materials never reach EMC in a house because the T and RH environment that surrounds the material is constantly changing due to a combination of climate, occupant moisture production, and the occupant use of HVAC.

After the taping and finishing process, screw number 1 (at the left bearing) and number 29 (at the right bearing) establish a common dimension between the 2x4 bottom truss chord and a 28-ft. width of "tape-connected drywall paper" on the bottom side of the panels. After the joints are finished, hygroscopic-induced differential strains between the entire 2x4 chord length and the finished drywall panel assembly produce strains and stresses in the taped connections (or edge joints) between the seven ceiling panels.

As an analogy, the two materials (lumber and drywall) are "married" by the shear transfer action of the screws connecting the truss chords and drywall. The shear transfer action of the screws in the plane of the ceiling is beneficial in that the drywall ceiling is permitted by the model codes to be used for lateral bracing of the bottom truss chords; however, an unintended consequence of the screws is the potential for drywall joint cracks.

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Longitudinal Shrinkage and Expansion of Lumber

The longitudinal shrinkage and expansion coefficient of lumber has been measured and reported by researchers for at least 75 years. According to the 2010 *Wood Handbook*[2], the *average* value of longitudinal shrinkage varies from 0.1% to 0.2% in drying from 30% MC to 0% MC (based on samples of 40-inch long lumber). It is also well documented that a sample of "juvenile" wood can shrink up to 10 times the average for "mature" wood. The demarcation between "juvenile" wood and "mature" wood is gradual and varies from piece to piece for any species.

As shown in Figure 2 from Jozsa and Middleton[3], juvenile wood is centered on the pith of the tree and encased by mature wood. They state that the "merchantable stem would contain about 50% juvenile wood by volume." Because of the obvious taper of the mature wood, most of the pieces of lumber manufactured from the tree (or log) would contain some amount of juvenile wood.

In terms of the possibility of a 100% mature lumber supply, it is not possible on a practical basis because the transition from juvenile wood to mature wood in a single piece of lumber requires a microscopic investigation. Likewise, it is not possible to specify and purchase commercially available lumber free of juvenile wood. Homebuilders and Architects of Record (hereafter, Architects) should assume that, when solid-sawn ceiling joists or MPC wood trusses are specified, the lumber used to support a drywall ceiling will contain some fraction of juvenile wood ranging from 0% to 100%.

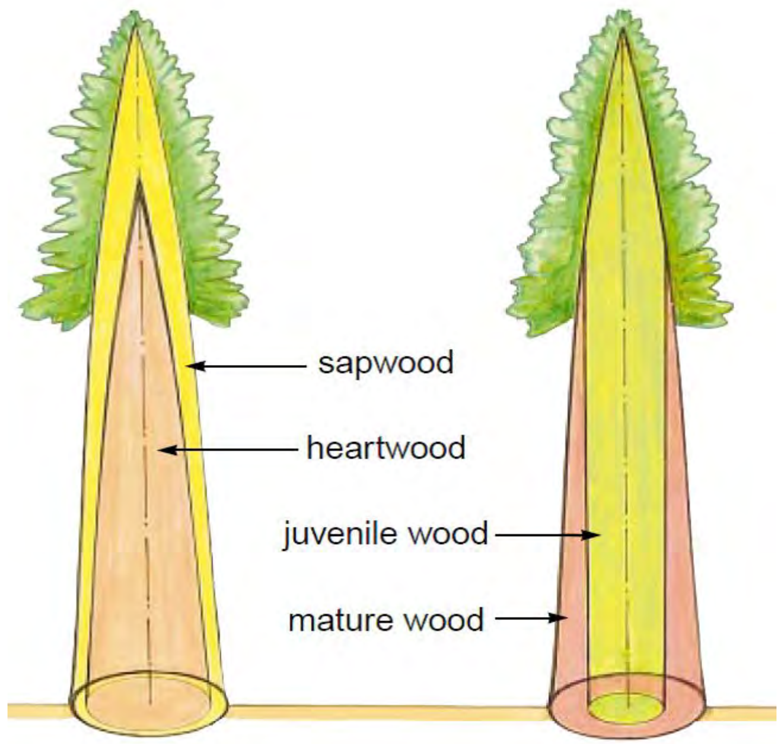

Figure 2. Depiction of juvenile and mature wood in 50-year old Douglas-fir tree from Jozsa and Middleton.[3]

Dimensional Stability Drywall—A Pilot Study

Materials and Testing Methodology

A single value for dimensional stability of drywall[4] as affected by changes in RH has been reported in the gypsum board technical literature for decades; however, the literature does not give the direction (4-ft. width or length direction) to which the coefficient applies. As stated earlier, because of the use of paper in the manufacture of drywall, one would expect some difference in the two directions, hereafter width (W) and length (L). By reviewing the literature for testing drywall, we noted that ASTM C 473–07[5] does not include a dimensional stability test method for the W and L panel directions. As such, our test method design was guided by ASTM standards applicable to wood-based panel products. Information contained in ASTM C 473–07 also provided valuable input for our testing methodology (described later).

We purchased two 4x8 ft. panels from a local supplier of interior gypsum board—one panel was 1/2" thick and the other was 5/8" thick Type X (nominal). From each 4x8 ft. panel, we cut 8"x24" specimens from the W-direction and L-direction. In each case, the W and L specimens were cut from the center area of the panel to

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avoid a potential "edge effect." Our test specimens will be referred to as W(1/2), L(1/2), W(5/8), and L(5/8). We noted that the 5/8" Type X panel contained a substantial amount of what appeared to be fiberglass fibers embedded in the gypsum core.

We inserted two hollow pins into the tests specimens to establish a test gauge length of approximately 19.75 inches. An adhesive was added to the hollow pins in the drywall specimens to secure the pins from slight movement. The specific details of the measurements techniques and equipment are given in Loferski[6].

The drywall specimens were placed into a conditioning chamber that maintained 75°F and 80% RH. After 26 days, the specimens were removed one at a time and the distance between the pins was measured. This measurement established the initial length of the specimen for the 75°F and 80% RH environment. The 26-day conditioning period ensured that the drywall specimens had reached EMC.

After recording the initial gauge lengths for each specimen, the specimens were placed into another conditioning chamber set to maintain 75°F and 27.5% RH. We did not change the chamber temperature of 75°F so as to remove any effects of temperature on the drywall response to the tested change in RH.

Dimensional Stability Testing Results

The specimens reached EMC in 13 days and the length change data are plotted in Figure 3. The x-axis in Figure 3 starts at zero and corresponds to the day that the specimens were removed from the 80% RH chamber and placed into the 27.5% RH chamber. The y-axis gives the percent change in length of each specimen on the testing day after being placed into the 27.5% RH chamber. The formula used for %-Shrinkage was:

%-Shrinkage = 100(Length on Day Measured-Initial Length)/Initial Length

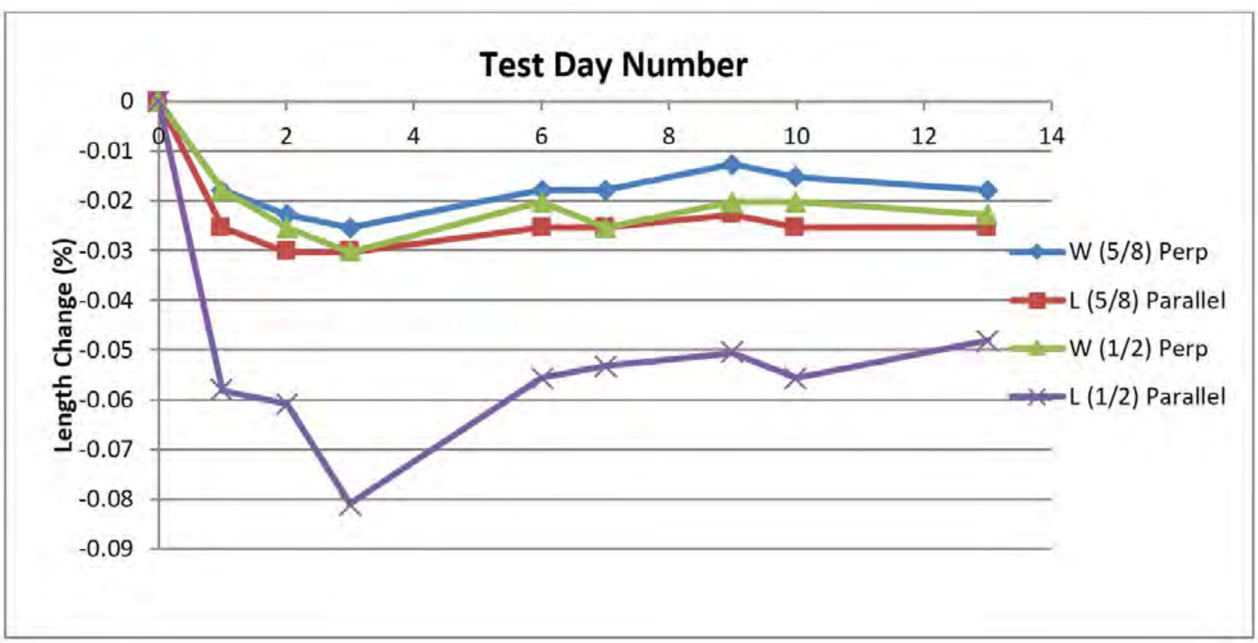

Figure 3. The "W" specimens were used to measure shrinkage in the panel width dimension and the "L" specimens were used to measure shrinkage in the panel length dimension. The specimens were conditioned at 75°F and 80% RH, and then placed into a chamber set to maintain 75°F and 27.5% RH.

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We were surprised by the results, because the panels did not reflect the typical behavior of paper discussed earlier. The pilot study results were indeed instructive in that substantial bi-directional behavior was observed for the 1/2-inch specimen and the fact that the *stabilized length* of the L(1/2) specimen at 13 days when reaching an equilibrium condition at 75°F and 27.5%RH was substantially more than the length at 3 days.

Milner and Adam[7] report a similar "spike type behavior" in drywall joint rotation from their 1999 full-scale laboratory study with wood trusses. Their comment on the movement of plasterboard is: On the other hand, plasterboard expansion seems to be affected by moisture uptake in the outer cardboard layers that tends to exchange moisture quite rapidly."

Apparently, at least some gypsum panel products react to a sudden change in RH and subsequently adjust to a final state, most likely due to redistribution of stresses and strains in the panel product. Obviously, the two panels tested in our pilot testing program may not be representative of the large number of drywall panels available in the marketplace.

The "spike type behavior" of all specimens at approximately three days is very important for understanding the potential impact of sudden RH changes on the formation of drywall joint cracks. Anecdotal evidence indicates that cracks and recurring cracks are observed at the same time the occupants activate their HVAC units when transitioning from one season to another. In terms of predicting the occurrence of a joint crack, it appears to us that the most useful test data to be collected would be the spike or maximum change in panel width or length based on an industry standardized RH change.

We compared the shrinkage rate of our test specimens to the typical shrinkage rate published by the Gypsum Association. Referring to Table 1, the maximum shrinkage response and stabilized shrinkage responses are tabulated in the second and third columns, respectively. The typical shrinkage rate from GA-235-10 is listed in the fourth column. The last column gives the ratio of the maximum response rate (MRR) for each test specimen to the typical value of -6.5x10-6 (in./in./%RH).

Table 1. Pilot study shrinkage rates were derived from the data in Figure 3 by dividing by the change in RH test conditions to yield a coefficient that can be compared to a typical rate from GA-235-10.

Specimen	Maximum RH Response Rate (MRR) in./in./%RH	Stabilized RH Response Rate (SRR) in./in./%RH	Published* RH Response Rate (PRR) in./in./%RH	Ratio of MRR To PRR
W(5/8)	-0.00000483	-0.00000338	-0.0000065	0.74
L(5/8)	-0.00000578	-0.00000482	-0.0000065	0.89
W(1/2)	-0.00000579	-0.00000434	-0.0000065	0.89
L(1/2)	-0.00001543	-0.00000916	-0.0000065	2.37

* GA-235-10 Gypsum Board Typical Mechanical and Physical Properties.

Our pilot test results demonstrated how a "typical shrinkage rate" does not predict the dimensional stability for both directions (W and L) of a specific product and points to the need for product-specific dimensional-stability data for use by Homebuilders and their Architects. From the perspective of a design professional

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concerned about in-service cracking potential, we suggest that the drywall manufacturers consider a "dimensional stability rating system" whereby different products would be tested and rated based on an average and maximum (spike type) shrinkage rate for both directions, W and L.

Significant Effects of Climate and Occupants

MPC wood trusses have been used widely throughout the United States for at least 50 years with no reports of ceiling joint cracks outside of some arid regions. While lumber and drywall hygroscopic properties may have changed over the decades, we are not aware of any reason or even possibility for arid regions of the Southwest to have utilized an "atypical" supply of lumber and/or drywall. The standard for truss design is a national standard and the same type of connections is used nationwide. The methods of roof truss framing in arid regions are the same methods used on other climates. The methods and materials used by drywall contractors can be eliminated as a cause of recurring cracks because some homes are known to have been repaired by different drywall contractors, yet cracks recurred. Therefore, it can be concluded that an arid climate is the single factor necessary for the potential occurrence and recurrence of ceiling joint cracks perpendicular to the truss or framing span.

The natural behavior of the occupants helps us to understand and explain the occurrence of ceiling cracks in some units, but not others. In one large residential project, with hundreds of *seemingly identical units*, some homeowners reported ceiling cracks while the majority of homeowners did not. The different outcomes for seemingly identical units in the same project points directly to the role of the occupant in terms of moisture production and the management of their HVAC system.

Based on residential environmental research by Aoki-Kramer and Karagiozis[8], a typical family of four produces between 9 and 31 lbs./day of moisture. To put that data in perspective, consider as one extreme the maximum daily rate 31 lbs./day. In one month, the family would produce 31 lbs./day x 31days, or 961 lbs. of water in the form of moisture vapor. In two months, the production would be 1,922 lbs.–just about a ton. Assuming the AC is not turned on and that windows are not used for ventilation, 1,922 lbs. of water must escape through the doors, walls, and ceiling. Of the vapor that is transmitted through the ceiling, it first encounters the drywall, then the bottom chord, then the insulation above. Because the attic is typically very dry except for isolated times, the vapor pressure (vp) in the house is substantially greater than vp of the air in the attic above the insulation. Other than the higher vp in the drywall, the next highest vp level is at the interface between the top of the drywall and the bottom of the bottom chord.

During the Summer season, the AC would be operating and the consequences of producing 31 lbs./day of moisture would likely be minimal because the AC serves as a dehumidifier. However, at some time in the Fall season, the AC can be turned off for comfort and "quiet" living. It is our understanding that, in some arid climates, neither AC nor heat is used for one or two months. Assuming a high moisture production family, the end result of the AC/Heat OFF scenario would be a substantially hydrated 2x4 chord which could easily occur in a month or two. The hydrated chord will tend to stretch the taped joint and, at some point, it may crack. Even if the taped joints survive the AC OFF period, the next seasonal trauma would be the Heat ON event. Turning the heating system to ON will cause a rapid drop in RH and a corresponding shrinkage of the drywall assembly. Based on anecdotal evidence, turning the heat ON for the first time after construction or the first time in a given heating season can trigger the cracked-joint event.

Considering the other extreme when the family is assumed to produce only 9 lbs./day of moisture instead of 31 lbs./day, one would expect the differences in drywall expansion and bottom chord expansion during the change of seasons to be substantially muted and thereby avoiding the joint cracking event.

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In summary, the two factors that separate homes across the U.S. that do not experience seasonal drywall joint cracks and the ones that do experience joints cracks are climate and occupant issues (moisture production and management). Unfortunately, without research to develop advanced hygrothermal/mechanical simulation models, it is currently impossible to predict which homes and occupants in an arid climate will likely experience cracks and which homes and occupants will likely remain crack free.

Conclusions

Unpredictable Nature of Ceiling Drywall Cracks

The differential movement between lumber and a drywall ceiling assembly that can produce a drywall joint crack is driven by climate, daily moisture production by the occupants, and occupant management of the HVAC system. Hourly weather data and corresponding moisture production history of the occupants are obviously unpredictable and can't be controlled by the Homebuilder and Architect. When the inherent variability of the framing lumber and drywall used to construct a specific residence is coupled with the unpredictable nature of weather sequences and daily moisture production by occupants, it is impossible to predict at the design stage whether or not joint cracks will form during the service life of the residence.

Direct Cause of Drywall Ceiling Joint Cracks

The direct cause of drywall ceiling joint cracks is most easily understood by posing a hypothetical case in a Southwest arid location where some homes have experienced the joint crack problem. Imagine a single-story 1,600 ft.^{2} home framed with MPC roof trusses that was purchased and occupied by a specific retired couple. In addition, assume that the homeowners experienced ceiling cracks in the living/dining area within the first year and the cracks recurred after being repaired. Based on our understanding of the mechanism and factors that produce drywall ceiling cracks, we can conclude: if the identical 1,600 ft^2 home design were constructed in Florida (or in any non-arid location) by the same subcontractors and purchased by the same couple, the ceiling cracks would not have occurred. This conclusion is based on the fact that cracks at drywall ceiling joints (perpendicular to wood framing) have never been reported in any non-arid location in the United States. It should be noted that the lumber species groups and grades, framing plans, and drywall installation standards and methods used in arid regions of the Southwest are also used in non-arid regions of the US.

Design Considerations for the Homebuilder and Architect

While new and related information is being developed for preventing ceiling drywall cracks, Homebuilders and their Architects should explore drywall installation details that may accommodate the differential hygroscopic movement between ceiling drywall and truss bottom chords (or ceiling joists). One possibility is to specify framing directions that minimize the maximum lengths of uninterrupted drywall parallel to the truss spans. Ceiling drywall finished joints (without control joints) should be inherently more vulnerable to greater differential hygroscopic movement between the lumber and drywall assembly when the drywall is directly attached and the framing span between the walls is greater.

Another option to consider for current construction is the specification of resilient channel (RC). Based on a study conducted in the late 1990s and summarized in Walls & Ceilings[9], Campbell states:

> "However, the most effective way to prevent the seasonal cracking is to use resilient channel to buffer drywall panels from truss movement. Jundt reported that installing resilient channel provided the only effective means of remedying problems in troubled homes, and that—as a preventative measure—it's a relatively cheap and practical way of keeping problems at bay."

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Lastly, the potential benefits of following the recommendations in Section 4.7.3 of GA-216-2010[10] for control joints can't be overstated. It should be noted that GA-216 has been a "Referenced Standard" in the International Building Code® since 2000.

Notes

1. Visit http://www.fpl.fs.fed.us/documnts/pdf1988/caulf88a.pdf.
2. Visit Chapter 4, http://www.fpl.fs.fed.us/products/publications/several_pubs.php?grouping_id=100&header_id=p.
3. Visit https://pdfs.semanticscholar.org/57b5/7386b0f5029e60812695c70ac34eb624069b.pdf.
4. See https://www.americangypsum.com/sites/default/files/documents/GA-235%20Gypsum%20Board%20Typical%20Mechanical%20and%20Physical%20Properties.pdf , page 6 of 8, "DIMENSIONAL STABILITY, Hygrometric Coefficient of Expansion."
5. See ASTM C 473–07 Standard Test Methods for Physical Testing of Gypsum Panel Products, ASTM (2009), Volume 04.01.
6. See "Exploratory study of bi-directional dimensional stability of gypsum panels" by J. R. Loferski, Wood Science & Forest Products Dept., Virginia Tech, Blacksburg.
7. See "Plasterboard peaking and cracking under timber roof trusses" by H. R. Milner and C. Y. Adam. 1999, Monash Engineering Timber Centre, Monash University, Australia.
8. Aoki-Kramer, M. and A. Karagiozis. 2004. New Look at Residential Interior Environmental Loads. ASHRAE, Buildings IX. 10p.
9. Campell, Greg. 2001. Drywall Cracking on a Global Scale. Walls & Ceiling, March 9th.
10. Visit https://gypsum.org/2019/04/ga-216-2018-application-and-finishing-of-gypsum-panel-products/.

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