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ACOUSTIC COMPARISON AND EVALUATION OF WALL STRUCTURES IN TIMBER CONSTRUCTION TO IMPROVE THE SOUND INSULATION IN THE LOW-FREQUENCY RANGE

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ABSTRACT

The quality in housing that is required nowadays has increased enormously over the years. Sound insulation, especially in the low-frequency range, is of particular importance. Sound investigations are therefore carried out in the extended frequency range between 50 to 5.000 Hz. Interference immissions between apartments or office rooms occur mainly in the range between 50 and 160 Hz. Therefore, airborne sound measurements - according to EN ISO 10140-2 - are carried out on party walls and walls to technical facility rooms built in wood frame and solid wood construction. The objective of the investigations is to modify the wall structures in such a way that sound insulation in the low-frequency range is significantly improved in lightweight structures. The effects of resonance frequency, mass and bending stiffness of the materials as well as the number of layers and spacing of layers with or without cavity insulation are investigated and assessed. The evaluation refers to the single-number value by taking into consideration the spectrum adaptation term C_{tr} in the extended frequency range. Our sound measurements have shown that the same single-number values are perceived differently. Consequently, small changes in the component structure can produce significant improvements in the low-frequency range.

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1. IMPROVEMENT MEASURES FOR AIRBORNE NOISE IN THE LOW-FREQUENCY RANGE

In timber construction, the components always consist of several layers (multi-layered), as the mass per unit area required for airborne sound insulation (about 400 kg/m²) is hardly achievable for single-layer components due to economic and resource efficiency. Because of the multi-shell design (mass-spring-mass system), sound needs to penetrate multiple resistance layers and, in this way, the required sound insulation level is achieved. While the sound insulation of single-shell building components (e.g. reinforced concrete) is only based on their mass and bending stiffness, in timber construction comparable sound insulation values can be achieved with significantly lower masses per unit area through intelligent multi-shell structures with flexible shells (mass) and corresponding cavity damping with fibre insulation materials (spring). When evaluating sound insulation, apart from the building component itself, the building situation and the component connections are decisive as well. This means that in addition to the sound-insulating properties of the partitioning component, the secondary sound paths (flank transmissions) must also be taken into consideration and evaluated.

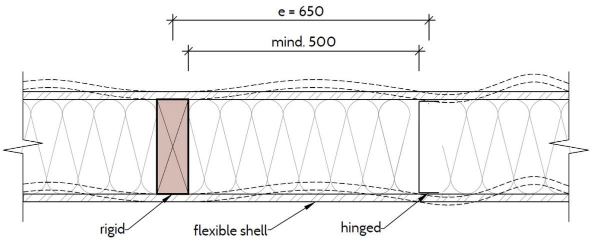


Figure 1. Application of the mass-spring-mass model - rigid and hinged connection of a flexible shell.

2. FREQUENCY RANGE

Solid wood elements made of cross laminated timber or glulam usually have a thickness ranging from 8 to 22 cm. This creates an unfavorable coincidence frequency in single-shell components and they are also flexurally stiff and have a low mass. For structures with a flexurally stiff, lightweight shell, it is particularly important that the second shell is flexurally soft and has as high a mass per unit area as possible. In order for the flexible materials to have an acoustic effect, several criteria must be considered. The distance between the supporting elements (solid wood, battens or C-profiles of the facing shells) must be at least 500 mm, so that the flexible shells can "swing". The spacing of the shells and the insulation material used are further essential points to consider. The oscillation system of a double-shell structure has a resonance frequency (natural frequency) at which the sound insulation drops sharply.

2.1 Resonance frequency f_{res}

The resonance frequency f_{res} can be determined with the following formula:

$$f_{res} = \frac{1}{2 \cdot \pi} \cdot \sqrt{s' \cdot \left(\frac{1}{m'_1} + \frac{1}{m'_2}\right)} \quad \text{[Hz]} \qquad (1)$$

- m'_1 Mass of the 1st shell [kg/m^2]
- m'_2 Mass of the 2nd shell [kg/m^2]
- s' Dynamic stiffness [MN/m^3]

The facing shells only bring about a sound insulation improvement opposite single-shell components, if the resonance frequency f_{res} of the double-shell system as low as possible. Therefore, f_{res} should be below the building acoustic frequency range (< 100 Hz), at least at 80 Hz or lower. The resonance frequency of a double-shell system depends on the mass of the shells, the distance between the shells and the dynamic stiffness of the insulation layer.

2.2 Dynamic stiffness s'

Dynamic stiffness s' is the resistance of a spring to an interaction of forces. Dynamic stiffness results from the dynamic modulus of elasticity and the thickness of the insulation layer or from the bulk density and the propagation velocity of the air, as well as the shell distance of the component layers. The lower the dynamic stiffness, the greater the springing capacity. The dynamic stiffness should be as low as possible so that the resonance frequency is below the range relevant to building acoustics. It is given in MN/m³. This means that the thickness of the insulation layer also plays a vital role. For airborne sound insulation of wall components, the dynamic stiffness of the insulation layer should be in the range of 2 to 5 MN/m³. This is similar to the stiffness of air.

The tuning of the component layers in relation to the resonance frequency is usually not sufficient for superior sound insulation requirements, so that the sound insulation quality does not quite meet to the A-weighting curve or human perception comfort in the low-frequency range. The subjective perception of the quality of sound insulation in the low-frequency range is indicated by the spectrum adaptation value C_{tr} (tr = urban traffic noise).

2.3 Spectrum adaptation value C_{tr}

The spectrum adaptation value C_{tr} is a value in decibels [dB] that is added to the singular value according to ÖNORM EN ISO 717-1 in order to include the characteristics of certain sound spectra, such as urban road traffic noise, low-speed rail traffic, jet aircraft noise at long distances, disco music, etc.

Multi-layered flexible materials with a mass per unit area layer > 15 kg/m² (special gypsum plasterboard or gypsum fibreboard, cardboard panels with quartz sand) have a particularly strong effect to improve the low-frequency range. Supporting profiles with a high springing capacity together with heavy-flexible planking in the widest possible spacing of the shells provides the best sound insulation quality in the deep frequency range.

The examples presented in the following section show the effects of individual building component layers on sound insulation in the low-frequency range. In addition to the standard single-number values R_w, the assessments of the sound tests primarily refer to the sound insulation values with the spectrum adaptation values in the frequency range from 100 to 3150 Hz ($R_w + C_{tr,100\text{-}3150}$) and in the extended frequency range from 50 to 5000 Hz ($R_w + C_{tr,50\text{-}5000}$).

The sound tests were carried out on party walls, external walls and on partition walls adjacent to building services rooms (technical walls) in one's own unit of use.

3. TIMBER FRAME CONSTRUCTION

3.1 Party walls (raw elements)

The acoustic investigations for improving the low-frequency range started with the timber frame construction elements. In the first step, the airborne sound of the basic elements (raw elements) with continuous (W.01 and W.03) and separate uprights (W.02 and W.04) were measured. The outer frame of the wall elements in both variants consisted of a solid structural timber beam with a cross-section of 60 mm width and 200 mm depth. The inner uprights in the separated variant were installed with depths of 100 mm and 80 mm. This means that there was a gap of 20 mm between the uprights. The basic elements were covered with OSB (oriented strand board) on one side and DWD (diffusion-open wall and ceiling board) on the other side. In order to determine the influence of the insulation material on sound protection in the low-frequency range, two series of measurements were carried out and the results were compared. In the case of the wall constructions W.01 and W.02, the cavity was damped with wood fibre. In the case of wall elements W.03 and W.04, the same structure was damped with mineral wool. Resulting from the higher density, the mass per unit area of the wall construction with wood fibre (36 kg/m²) was slightly higher than that of the construction with mineral wool (31 kg/m²).

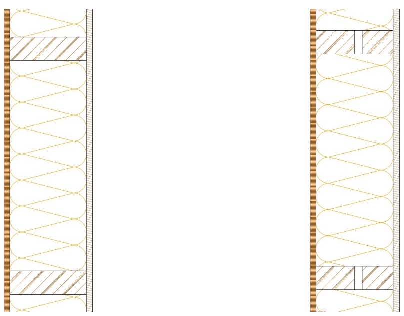


Table 1. Wall constructions in timber frame - basic elements with continuous uprights (W.01 and W.03) or separate uprights (W.02 and W.04).

Wood fibre	**W.01**	**W.02**
R_w	48 dB	53 dB
$R_w + C_{tr,100\text{-}3150}$	34 dB	45 dB
$R_w + C_{tr,50\text{-}5000}$	31 dB	33 dB
Layers	OSB - HF - DWD	OSB - HF - DWD
Mass per unit area	36 kg/m^2	36 kg/m^2

Mineral wool	**W.03**	**W.04**
R_w	50 dB	52 dB
$R_w + C_{tr,100\text{-}3150}$	38 dB	44 dB
$R_w + C_{tr,50\text{-}5000}$	28 dB	33 dB
Layers	OSB - MW - DWD	OSB - MW - DWD
Mass per unit area	31 kg/m^2	31 kg/m^2

Table 1. shows the functional layers (materials used) and the sound reduction indexes R_w with and without spectrum adaptation values C_{tr}.

The sound tests showed that there were already significant quality improvements in the low-frequency range in the raw elements with separately installed uprights. These improvements were also perceived subjectively in the course of the investigations. In other words, the noise level was so low that a feeling of comfort could be experienced. In the measurement series with wood fibre insulation (W.01 and W.02), the airborne sound in the low-frequency range improved for $R_w + C_{tr,100\text{-}3150}$ by 11 dB and for $R_w + C_{tr,50\text{-}5000}$ by 2 dB respectively. In the standard measurements R_w without spectrum adaptation values C_{tr} the difference was 5 dB. In the measurement series with mineral wool (W.03 or W.04), the improvement in the low-frequency range was 6 dB and 5 dB respectively. However, in the standard measurements R_w without spectrum adaptation values C_{tr}, the difference was only 2 dB.

The test results also showed that the standard single-number value R_w of the wall construction with continuous uprights and mineral wool was slightly higher, i.e. better, than that with wood fibre. For the rest, the measurement results for the constructions with wood fibre and mineral wool were very similar, especially for the variant with separated uprights. This means that the insulation type has no significant influence on the sound protection in the low-frequency range. The reason for this is that both insulation materials (wood fibre and mineral wool) have the same amount of fibre content and similar air flow resistance.

If it is possible for static reasons, elements with separate uprights should be preferred for improving the low-frequency range, because higher sound insulation values can easily be achieved in this way.

3.2 Party walls with facing shell

In a further step, the two basic elements with wood fibre insulation (W.01 or W.02) were measured with an additional facing shell. A double planked gypsum fibre / quartz sand board (12.5 + 15 mm) with C-profiles on a swinging bracket and wooden substructure (W.05) or metal CW-profiles (W.06) and a shell distance of 50 mm was used for the facing shell. The cavity of the facing shell was damped with mineral wool. The two spring systems behaved very similarly and led to the same sound improvement.

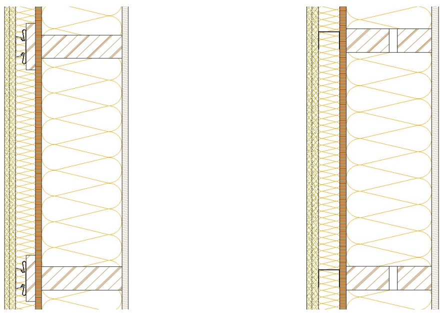


Table 2. Wall constructions in timber frame

Structures	W.05	W.06
R_w	67 dB	71 dB
$R_w + C_{tr,100\text{-}3150}$	51 dB	54 dB
$R_w + C_{tr,50\text{-}5000}$	36 dB	45 dB
Layers	SF - SBM - OSB - HF - DWD	SF - SB - OSB - HF - DWD
Mass per unit area	77 kg/m^2	77 kg/m^2

The facing shell improved the standard single-number values R_w when compared to the raw elements by 19 dB for the construction with continuous uprights and 18 dB for the variant with separate uprights. The resonance frequency of the facing shell was f_{res} = 90 Hz. This resulted in a calculated improvement ΔR_w of about 18 dB. The result of the calculation thus agrees very well with the measurement results.

In the case of the timber frame construction elements with facing shell (W.05 or W.06), the airborne sound insulation in the low-frequency range improved for $R_w + C_{tr,100\text{-}3150}$ by 3 dB and for $R_w + C_{tr,50\text{-}5000}$ by 9 dB respectively. For the standard measurements R_w without spectrum adaptation value C_{tr} the difference was 4 dB. A noticeable improvement was therefore evident.

The sound test results of the party walls showed that the standard single-number value R_w was on average 2 to 5 dB better with separate uprights than with continuous uprights. The sound improvements were mainly in the low-frequency range.

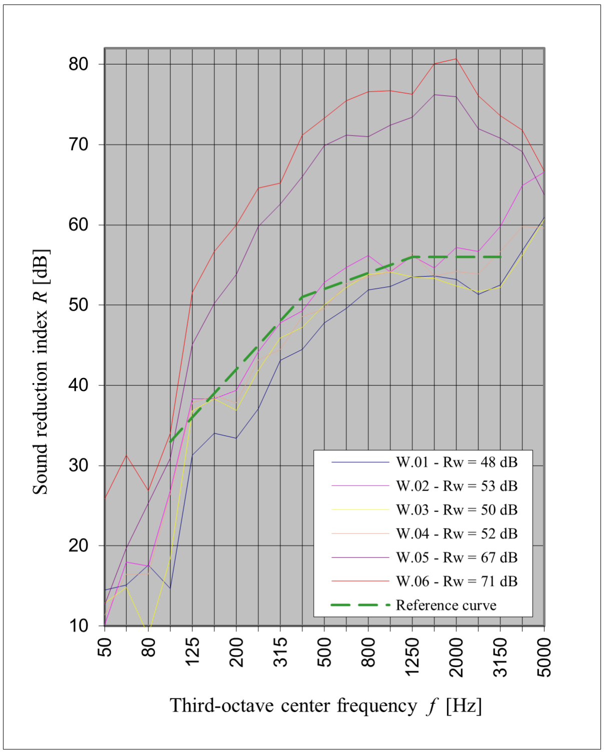


Figure 2. Diagram 1. - Measurement curves (W.01 - W.06)

Diagram 1 shows the measurement curves of the tested timber frame partition walls (W.01 to W.06) in the extended frequency range from 50 to 5000 Hz. For a qualitative sound insulation assessment, it is necessary to consider the entire acoustic range of the building. The diagram shows the potential for improvement from the basic elements (W.01 to W.04) to the optimised adaptation of the party walls with additional facing shell (W.05 and W.06).

3.3 Walls adjacent to technical rooms (technical walls)

For the acoustic investigations of partition walls adjacent to technical rooms in one's own unit of use, the same basic timber frame element with separate internal uprights was used as for the party walls. A 15 mm sound insulation board with quartz sand (m' = 22 kg/m²) was installed between the separated uprights (20 mm gap). During installation, care had to be taken that the board was not clamped and remained flexible in the area of the uprights, unless the clamping was necessary for static reasons. The outer planking of the technical wall W.07 consisted of an OSB on one side (m' = 9 kg/m²) and an OSB and a high-quality gypsum plasterboard on the other side (m' = 12.8 kg/m²). In contrast to the technical wall W.07, with the technical wall W.08 a high-quality gypsum plasterboard was additionally attached to the single planked side and the OSB was replaced on the other side by a sound insulation board with quartz sand (m' = 22 kg/m²). This increased the mass per unit area by 26 kg/m². The cavities between the planking were filled with mineral wool and wood fibre. Two different insulation materials were only used, because they were available on site in the respective insulation thickness. The sound tests carried out in the timber construction department showed that the sound insulation value tends to be slightly higher when mineral wool is used.

With the technical wall W.07 and the technical wall W.08, with only one replaced shell and an additional component layer (12.5 mm plasterboard, high quality), the airborne sound in the low-frequency range improved for $R_w + C_{tr,100\text{-}3150}$ by 7 dB and for $R_w + C_{tr,50\text{-}5000}$ by 5 dB respectively. For the standard measurements R_w without spectrum adaptation values C_{tr} the difference was 8 dB.

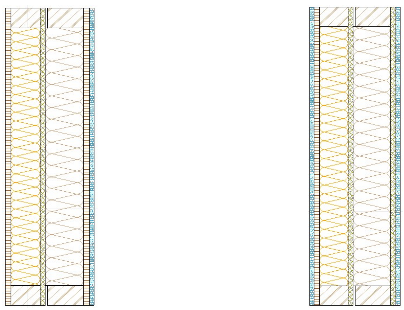


Table 3. Technical walls (timber frame)

Structures	**W.07**	**W.08**
R_w	55 dB	63 dB
$R_w + C_{tr,100\text{-}3150}$	51 dB	58 dB
$R_w + C_{tr,50\text{-}5000}$	39 dB	44 dB
Layers	OSB - MW - SK - HF - OSB - GKFI	GKFI - OSB - MW - SK - HF - SK - GKFI
Mass per unit area	61 kg/m²	87 kg/m²

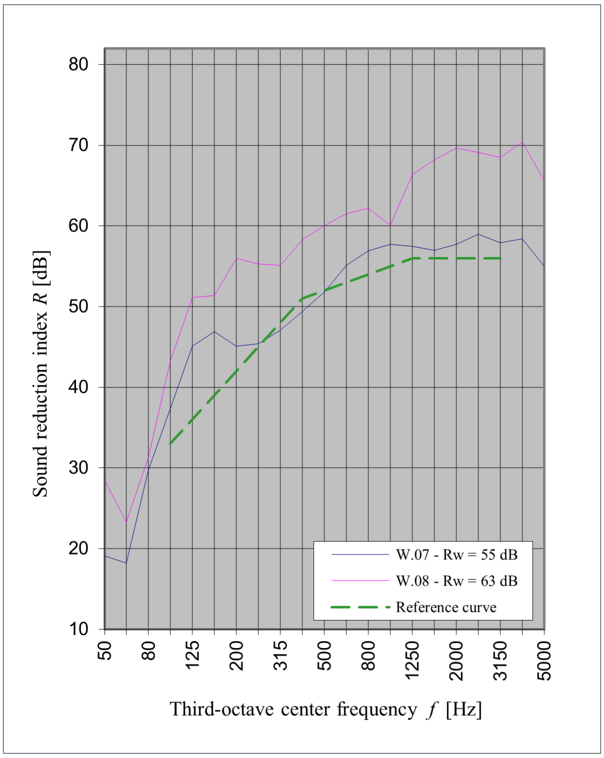


Figure 3. Diagram 2. - Measurement curves (W.07 - W.08)

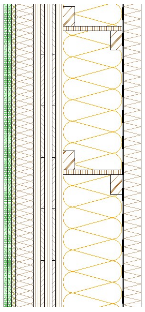
As already mentioned, especially the high-grade gypsum plasterboards as well as the cardboard panels with quartz sand have a positive effect on the low-frequency range airborne sound.

4. SOLID WOOD CONSTRUCTION

4.1 Exterior walls

The exterior walls consisted of a 100 mm CLT panel (cross laminated timber) with two facing shells. On the inside of the solid wood wall, a triple planked facing shell (2x12.5 mm gypsum fibre board + 15 mm sound insulation board with quartz sand) was attached to a 60 mm wood fibre board. The facing shell on the outside consisted of 200 mm wood fibre insulation materials between Z-beams and varying planking.

For the exterior wall constructions in cross laminated timber construction, the deviations of the single number values R_w were in the range of the measurement accuracy (1 - 2 dB), i.e. in the standard measurements no sound quality difference was given. Compared to the spectrum adaptation value C_{tr}, however, there were improvements of up to 7 dB in the low-frequency range, depending on the measuring range. In addition, in the case of structures with cross laminated timber elements, it could be seen that flexible shells with a high mass per unit area lead to clearly perceivable improvements in the low-frequency range.



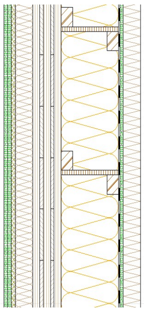


Table 4. Exterior walls (solid wood construction)

Structures	W.09	W.10
R_w	72 dB	73 dB
$R_w + C_{tr,100\text{-}3150}$	58 dB	65 dB
$R_w + C_{tr,50\text{-}5000}$	42 dB	48 dB
Layers	SL - SL - SK - HF - BSP - HF_ZT - PTA	SL - SL - SK - HF - BSP - HF_ZT - GF - PTA
Mass per unit area	152 kg/m^2	166 kg/m^2

When comparing the exterior wall W.09 and W.10 it was revealed that with only one additional component layer (12.5 mm gypsum fibre board, m' = 14 kg/m²) the standard single-number value R_w increased by only 1 dB. When taking into account the spectrum adaptation values (R_w + Ctr,100-3150), however, the airborne sound insulation improved by 7 dB and in the extended frequency range ($R_w + C_{tr,50\text{-}5000}$) by 6 dB.
The airborne sound quality of the exterior wall constructions with CLT was according to the single number values R_w, equally good (maximum 2 dB deviation). In the low-frequency range, however, there were perceptible differences in quality, both metrologically and subjectively in the acoustic lab, although all the structures featured high-quality sound insulation. The high sound insulation quality is also shown in the diagram. The measured values at 100 Hz are clearly better than the quality required in the reference curve. The reference curve is only shown in the building acoustics range from 100 to 3150 Hz, as this is also the range used to determine the single number value.

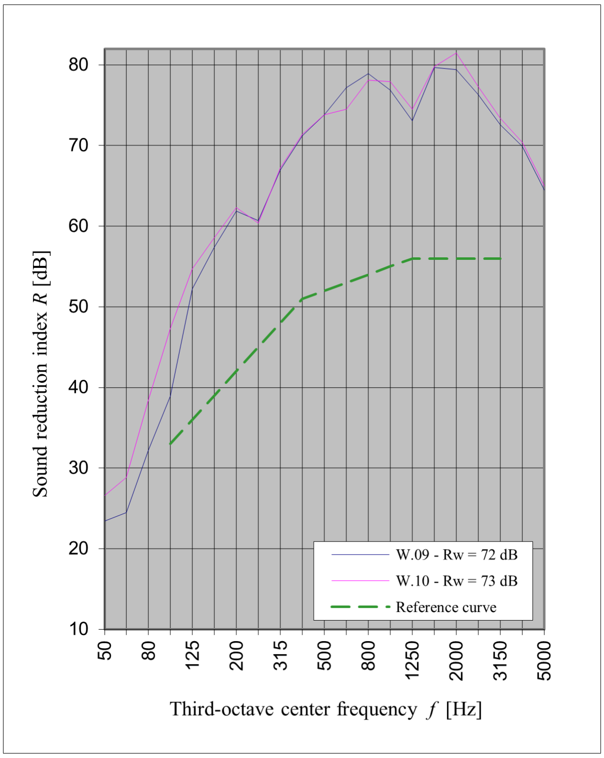


Figure 4. Diagram 3. – Measurement curves (W.09 - W.10)

5. FINDINGS OF THE ACOUSTIC INVESTIGATIONS

At the University of Innsbruck, more than 100 structures (party walls, partition walls adjacent to building services rooms – technical walls, exterior walls) have been investigated over the past few years, starting from the basic elements (cross-laminated timber element or timber frame element, single-sided, single-boarded), to determine the sound quality in the low-frequency range. The examples in this paper are intended to show that, on the one hand, it is possible to achieve a high sound insulation quality in lightweight construction, even in the low-frequency range, and, on the other hand, what impact individual material layers can have on the quality of sound insulation.

Table 5. Abbreviations

[mm]	Functional layers	Abbreviation
15	Oriented strand board	OSB
50	Mineral wool	MW
16	Diffusion-open wall and ceiling board	DWD
27,5	Gypsum fibre / quartz sand board	SF
50	C-profile on swing bracket	SBM
50	Metal CW profile	SB
15	Sound insulation board quartz sand	SK
200	Wood fibre	HF
	KVH 60/200, e = 625	
	KVH 60/100 + 80, e = 625	
200	Z-Beam (OSB + KVH 60/40)	ZT
60	Wood fibre insulation board	PTA
12,5	Gypsum board GKFI high quality	GKFI
12,5	Gypsum board GKF sound insulation	SL
12,5	Gypsum fibreboard	GF
100	Cross laminated timber	BSP

6. CONCLUSION

In lightweight constructions high sound insulation requirements in the low frequency range can be achieved if the following conditions are met: flexibility of the component layers with a high mass per unit area, low dynamic stiffness of the insulation layers and the adaptation to the resonance frequency.

7. REFERENCES

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